AN ANALYSIS OF

LIGHTNING LAUNCH CONSTRAINTS

THESIS

Donald E. Holland
Captain, USAF

AFIT/GSO/ENG/88D-1

DEPARTMENT OF THE AIR FORCE

AIR UNIVERSITY

AIR FORCE INSTITUTE OF TECHNOLOGY

Wright-Patterson Air Force Base, Ohio

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Air University

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Master of Science in Space Operations

Donald E. Holland, B.S.

Captain, USAF

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Preface

The purpose of this study was to review the current set of lightning launch constraints used by NASA, the United States Air Force, and the United States Navy. In particular, I wanted to look at the first constraint and the impact that it may have on launch availability.

I analyzed cloud-to-ground lightning in the Cape Canaveral area and found a very interesting spatial distribution that may impact launch availability. I also developed a model that simulates all types of lightning in the Cape area. From that model, I developed equations that describe the launch availability based on the first constraint. Though the model makes several assumptions about distributions, I think the model captures the essence of what is needed, and when other numbers are found for the distributions, they can by used.

This thesis would not have been possible without the help of several people. My advisor, Capt Randy Jost of the Electrical Engineering Department at the Air Force Institute of Technology at Wright-Patterson AFB, was a constant source of information that helped tie the pieces together. Col Matthew Nichols of AFIT/ENS always had encouraging words, and Maj Dave Stone of AFIT/ENP helped me get started and keep working on the simulation model. A special thanks goes to Col John Madura and his folks at Detachment 11, Second Weather Squadron at Patrick AFB. In addition to sponsoring my work, they provided prompt and accurate assistance. Capt Tom Strange and John Weems of Detachment 11 and Lt Col Tom Myers (formerly of Detachment 11) were particularly helpful with technical and historical information. Raul Lopez and Ron

Holle of NOAA's Environmental Research Laboratory in Boulder, CO provided much appreciated information about Florida lightning and suggestions for how to approach this thesis.

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Abstract

The purpose of this study was to review the current set of lightning launch constraints being used by NASA the U.S. Air Force and the U.S. Navy. The study had 3 primary objectives: (1) Assimilate current knowledge about triggered lightning to aerospace systems, and how lightning launch constraints are used to make launching safer. (2) Analyze cloud-to-ground lightning in the Cape Canaveral, FL, area for spatial and diurnal distributions and for its impact on launch availability. (3) Develop a model to simulate all lightning events to better determine launch availabilities based on the first constraint.

The study found that the lightning activity in the Cape area is not uniformly distributed in time or space. There is a well-known afternoon peak in activity, plus, there are areas where lightning occurs with much greater frequency--especially with low-level winds from the southwest. Since the launch constraints specify standoff distances and delay times from naturally occurring lightning, launch availability is a function of time of year, time of day, and launch site. From the simulation model, equations were derived to define launch availability as a function of standoff distance and delay time for each summer month (Apr-Sep) and each 3-hour group (e.g. 0000-0300 Local Standard Time) in July and August.

AN ANALYSIS OF LIGHTNING LAUNCH CONSTRAINTS

I. Introduction

This thesis reviews the set of lightning launch constraints that the National Aeronautic and Space Administration (NASA), the United States Air Force (USAF), and the United States Navy (USN) have accepted. It compares some of the old constraints with the new ones that NASA and the USAF accepted in March 1988 and the USN accepted in August 1988. The thesis makes some suggestions for analyzing the set as a whole and analyzes one of the six lightning constraints in detail. The major steps of this thesis effort were to:

a. Assimilate current knowledge about triggered lightning pertaining to launching space vehicles.

b. Develop a methodology that can be used when more data are available. The methodology includes an analysis of cloud-to-ground lightning in the Cape Canaveral Air Force Station (CCAFS) and Kennedy Space Center (KSC) area, and lightning's impact on launch availability.

c. Develop a computer simulation to model lightning of all types around CCAFS/KSC, and analyze the simulated data.

d. Formulate charts and equations defining the potential impact of changing one of the launch constraints.

e. Present and discuss the results of the analysis and make suggestions for future research.

Background

On 14 November 1969, as Apollo 12 was being launched to the moon, it was struck twice by lightning. Lightning first struck at 36.5 seconds into the flight and then again at 52 seconds into the flight (32:87). Although the damage was minor enough that Apollo 12 was able to go on to the moon and return safely to Earth, serious concerns were raised about the threat of electrostatic discharges to space craft. That danger was again realized on 26 March 1987 when an Atlas-Centaur rocket (AC-67) was struck by lightning when it was 48 seconds into its flight. AC-67 was destroyed as a result of that lightning strike.

After the loss of AC-67, the scientific community spent a great deal of time and effort in developing new lightning launch constraints that, if followed, would make space flight safe from the hazards of lightning. In March 1988, NASA and the United States Air Force approved a set of lightning launch constraints. The U.S. Navy approved the same set in August 1988. These new constraints call for the observation and use of more meteorological indicators and stricter adherence to being absolutely safe. Operational personnel, however, have had some concern that the conservatism of the constraints will unduly limit launch availability and restrict launch opportunity.

Lightning

Uman describes lightning as "a transient, high-current electric discharge whose path length is generally measured in kilometers" (42:1). Lightning occurs when the ambient electric charge in an area is sufficiently strong and the associated electric fields cause an electrical breakdown of the air. The total duration of a lightning discharge is on the order of a half of a second and can transfer tens of coulombs of charge. The transfer can occur in the cloud (in-cloud), from one cloud to another (cloud-to-cloud), from cloud to clear air (cloud-to-air) or from the cloud to the ground (cloud-to-ground). The usual location for lightning is in or near convective activity in the atmosphere. The charge separation that exists in the cumulus clouds enhances the electrical breakdown of the air. Lightning which lowers a negative charge to the ground is called a negative stroke (as opposed to a positive stroke which would lower positive charge to ground). Negative strokes are the more common cloud-to-ground stroke in summertime Florida storms. Positive strokes usually occur toward the end of the storm, are more common in winter, and account for about 15% of Florida lightning strikes (24).

Lightning is a severe hazard to many outdoor activities--particularly where flammable, combustible, or explosive materials are being handled. Lightning frequently causes work stoppages at Cape Canaveral Air Force Station and the Kennedy Space Center, especially in the summer. In addition to its impact on daily operations and launch preparations at CCAFS/KSC, the threat of lightning can delay launching of space vehicles.

Triggered Lightning

For the purposes of this thesis, a distinction is drawn between natural lightning and triggered lightning. Though, "in a sense, all lightning is triggered lightning" (5:117), triggered lightning is defined as lightning that would probably not have occurred had it not been for the presence of a man-made object. There is evidence that tall man-made structures such as towers or tall buildings receive more lightning strikes than would normally be associated with a given location (37:180). Also, Fisher, et al, report in the "Final Results of the NASA Storm Hazards Program," that significant numbers of lightning attachments to free flying aircraft can be shown to have originated on the aircraft itself (8:n.p.).

The methods that have been used to study lightning in general and triggered lightning in particular have included analysis of the lightning attachments to aircraft. Another method has been to attach a trailing wire to a small rocket and launch it into an area of the atmosphere known to be electrically charged.

Triggered Lightning and Aircraft/Spacecraft

The bulk of knowledge which exists about triggered lightning to free-flying vehicles comes from studying lightning attachments to aircraft. When an aircraft flies through the air--even clear air--it develops a charge on its skin. When it flies through water and ice clouds, it will charge even more. This is particularly true of dielectric materials which cannot dissipate the charge or conduct it away from the area of build up. As the airplane approaches a charged area of the atmosphere, such as a charged cloud, the potential difference between the cloud and the airplane causes a breakdown of the air and eventual lightning strike or discharge.

There are two factors which make triggered lightning more of a problem than it has been in the past. First, as mentioned above, the use of composite skin materials causes charge build up which provides an ideal point for a lightning attachment. When the discharge occurs, it can cause severe structural damage--such as destruction of the radome or a fuel tank explosion.

The second factor that causes lightning to be more of a threat is the use of more electronic systems on board. Mechanical and hydraulic systems are virtually immune to transient electric effects. Electronic systems, on the other hand, do not operate predictably in the presence of widely fluctuating electric fields such as those that accompany a lightning strike. AC-67 failed due to transient electric currents in the digital control unit (4:n.p.). Other than minor pinpoint burn marks, the lightning did virtually no significant structural damage to the rocket.

To reduce the threat of a triggered lightning strike, the operators of aerospace systems have two options: 1) avoid the threat area, or 2) harden the vehicle such that lightning strikes can be accommodated, or both. The subject of this thesis falls within the realm of threat avoidance.

Triggered lightning threats can be avoided in either space or time. A free-flying airplane can normally manuever around the area of threat--except during take-off and landing. A rocket, however, has a prescribed flight path which must be followed to attain the required orbital parameters. Any deviation from that path would be at least inefficient, and may be something that cannot be corrected later, causing mission failure. A rocket launch must therefore be timed such that the planned flight path does not intersect hazardous areas.

Triggered Lightning Avoidance

Lightning launch constraints stress the avoidance of potential danger. Typically, they prohibit launching through or near thunderstorms or other meteorological conditions that indicate potential electrical hazards.

Different constraints have been used by NASA, the Air Force, and the Navy as more has been learned about lightning. With the acceptance of a standardized set of constraints, there should be less opportunity for misunderstanding or misinterpreting the constraints in the future.

Problem

The overall goal of this thesis is to provide the framework for a systematic review and analysis of the current set of lightning launch constraints. Currently, due to lack of data, it is not possible to answer the following questions completely and quantitatively; however, the objective is to raise the questions and answer them to the extent possible. When more data are available, a more complete review will be possible.

Questions concerning the current set of lightning launch constraints include:

a. Do the constraints define the conditions that constitute a triggered lightning threat to aerospace systems?

b. What impact do the constraints have on launch availability?

c. How representative of the electric field aloft are the parameters that can be measured on the ground?

d. What impact would the use of an airborne electric field mill system have on adherence to the constraints?

e. Which constraints will delay launching the most, and should they be modified?

f. What other parameters might be important that are not addressed by the constraints?

Due to time limitations and lack of data, this thesis addresses only the second question in detail. The first question will require further study by the scientific community. At present, the constraints are the best that this country's scientists have to offer (41). The third and fourth questions require collection and analysis of airborne electric field measurements. The fifth and sixth questions require more data be collected before they can be answered.

Scope

There are six lightning launch constraints which require knowledge and measurements of different meteorological parameters. However, none of those parameters are routinely observed and reported weather phenomena, at least not in the form, and as specific as required by the constraints. Therefore, though weather observations have been faithfully collected for decades, they do not contain the weather parameters needed to analyze these constraints. Nor may they contain the parameters needed to verify whether a constraint is being violated at launch time.

One data base does exist from which partial answers to the problem can be derived. One constraint, concerning lightning within 10 nautical miles within the last 30 minutes, can be addressed using data from the Lightning Location and Protection (LLP) system at the Cape--in this thesis, "the Cape" refers to the CCAFS/KSC area. Data sources that can be used for the analysis of the other constraints are in various stages of development and collection. The time required for the collection of these data (perhaps several years in some cases) is beyond the chronological scope of this thesis.

All of the constraints were reviewed to show their evolution and how they complement each other. One constraint was analyzed in more detail using the data set from the LLP and a computer model of lightning activity in the CCAFS/KSC area. No effort is made to speak to the actual validity of the constraints under all possible meteorological conditions since all the physical processes involved in triggered lightning are not fully understood at this time.

Assumptions

There are several assumptions which must be made in order to review the constraints as a whole and analyze one constraint in particular. The key assumptions for the analysis are:

a. Cloud-to-ground lightning in an area is representative of the location of all types of lightning. LLP records only negative, cloud-to-ground strokes, and only about 80% of those are recorded, so only a sample set of lightning strikes is actually recorded. (Krider, et al, have estimated that each detector of an LLP network "detects 80-90% of all cloud-to-ground flashes" within 400 kilometers (107:208). Since operational users at the Cape believe that the network as a whole detects about 70-80% of cloud-to-ground flashes (41), this thesis assumes an 80% detection efficiency).

b. The diurnal and spatial variability of the lightning in the Cape area during the summers of 1983 and 1984 (the period of record for the data set) is representative of the variability during other summers at the Cape. I made no assumptions about the annual distribution of lightning activity from the summer data sets. More than two years of data would be needed to make those assumptions.

c. The recorded positions of the lightning strikes are correct. There are inherent errors associated with the LLP system; however, it will be assumed that in the data set used, all those errors have been accounted for and the final values are correct. Appendix A gives more information about the theory of the LLP network.

Approach

The approach of this thesis is to show how the lightning launch constraints tie together to make launching as free as possible from the hazards of triggered or natural lightning. A data set that can be used to evaluate one constraint was analyzed for spatial and diurnal characteristics of lightning around the Cape. I used climatology, previous research by other scientists and my own personal experience as a range meteorologist at the Cape to develop the basis for a lightning model. I analyzed the output of that model to develop charts and equations to estimate launch availability around the Cape.

Sequence of Presentation

Besides this introduction section, this thesis has 5 major parts (chapters). Chapter 2 deals with the background of the set of launch constraints. It discusses prior and current understanding of lightning and lightning's threat to space flight. It also shows where the current constraints came from, how they tie together, and how weather is observed at the Cape. Chapter 3 is a study/analysis of two years of actual cloud-to-ground lightning data from the LLP network at the Cape. I use that data to study the diurnal and spatial variability of lightning in the Cape area. In Chapter 3, I also analyze the data for launch availability considerations. Since the first lightning launch constraint deals with all types of lightning, and LLP data only provides information on a subset of cloud-to-ground lightning, I developed a model in chapter 4 that simulates all types of lightning activity around CCAFS/KSC. The output from that model is analyzed to estimate the percentage of lost launch availability due to lightning events. Chapter 5 is a discussion of the results and conclusions. Chapter 6 provides a summary of the work and recommendations for future research/study.

II. Background

On 28 January 1986, the space shuttle Challenger was launched from Cape Canaveral, Florida. Just over 73 seconds into the flight, a massive explosion destroyed the Challenger, its payload and crew of seven. The ensuing investigation decided that the cause of the accident was the failure of an O-ring in one of the solid rocket boosters to properly seal. The local temperature preceding and at launch time was a contributing factor causing the failure of that O-ring.

In February 1986, there was a Titan launched from Vandenburg which failed and a Delta launch failure from Cape Canaveral in May 1986. Finally, on 26 March 1987, an Atlas-Centaur (AC-67) launch vehicle was launched from pad 36B at Cape Canaveral Air Force Station (CCAFS). At about 48 seconds into its flight, the vehicle was struck by a triggered lightning strike and subsequently lost.

The investigations of the shuttle accident and AC-67 showed weather to be a factor. In the case of the shuttle, no launch criteria were violated and the temperatures were accurately forecasted 24 hours before launch. However, in the case of AC-67, a post launch analysis and interpretation of the constraints and data showed that one weather constraint was probably not met. Both accidents served to show the important role that weather and weather support plays in launching space vehicles.

The national concern over a grounded shuttle fleet, the loss of so many of the few remaining expendable launch vehicles (ELVs), and no viable alternatives caused considerable consternation about the United States' access to space. Safety was being stressed more than ever, but payloads were not getting into orbit. Against this backdrop, an increased awareness of weather emerged and new lightning launch constraints were developed.

History of Man's Understanding of Lightning and Triggered Lightning

Man's interest in lightning can be traced back several thousand years. Attempts to scientifically explain lightning date back to at least the sixth century B.C. when lightning was thought "to be flaming gas ignited by the collision and friction among clouds" or "fire originating from the sun or stars" (38:92-2). In 65 A.D., Lucius Annaeus Seneca compared lightning to small sparks similar to those produced by flints (38:92-2). In 1671, G. W. Liebnitz discovered the electric spark. Further work in the mid 18th century by Dalibart and Benjamin Franklin proved the electrical nature of lightning and that clouds carry an electrical charge (38:92-2).

This early work set the stage for further analysis and research into the development and structure of thunderstorms and lightning. However, lightning is still not a well-understood phenomenon. There is still no generally accepted theory which explains all the behavior of lightning.

Triggered lightning is even less understood. "Triggered lightning was first demonstrated tragically in 1752 when Russian physicist G. W. Richmann was killed attempting to repeat Benjamin Franklin's experiments" (32:87). In 1961, Brook, et al, reported that all attempts to trigger lightning by lifting several kilometers of piano wire via balloon directly into thunderstorms were unsuccessful. They then conjectured that if the wire were introduced into the storm rapidly, perhaps a triggered lightning strike would occur since the wire would not have time to slowly neutralize the electric field around it (2:3967). In 1965, Newman reported that he was able to trigger lightning by launching a small rocket with a thin trailing wire into the clouds (33:482). Active rocket triggered lightning programs (including one at KSC) have begun to help define and understand the lightning process.

Another type of triggered lightning (and the one of more interest in this thesis) is the lightning triggered by free-flying vehicles, e.g., airplanes and rockets. In 1969, the Apollo 12 rocket to the moon triggered two lightning strokes at 36.5 and 52 seconds into its flight (32:87). Prior to that, it was not generally believed an aircraft would trigger lightning--it was thought that when an aircraft was struck by lightning, it simply intercepted a naturally occurring lightning stroke. Even as late as 1982, there was "considerable debate and uncertainty regarding the possibility of aircraft triggered lightning. This was basically because there were no definitive measurements of aircraft triggered lightning and no physical models were developed to explain it" (35:48). However, at the conclusion of the NASA Storm Hazards Program which ran from 1980 to 1986, Fisher, et al, reported "the first instrumental proof . . . of aircraft-triggered lightning flashes originating at the aircraft" (8:n.p.).

A renewal of operational interest in lightning triggered by free-flying rockets occurred on 26 March 1987 when an Atlas-Centaur rocket

(AC-67) was struck by lightning. That event is described by Christian, et al:

> At approximately 48 seconds into the flight, the vehicle was struck by a triggered, cloud to ground lightning flash, comprised of at least four return strokes. The resulting lightning current apparently coupled a signal into the wiring which goes to the Centaur digital computer unit (DCU), which caused a single word memory alteration. The altered memory was associated with the computation of the Atlas engine yaw commands, and caused the DCU to issue a hardover engine gimbal command. This resulted in an excessive angle of attack, large dynamic loads and the breakup of the Atlas Centaur-67. (4:n.p.)

Mechanisms Responsible for Triggered Lightning

In 1982, there was no definitive proof an aircraft would trigger lightning (35:48), but it was realized that "in a sense, all lightning is triggered lightning, since some mechanism must initiate the response" (5:117). Two triggering concepts are presented by Clifford and Kasemir (5:119). The first concept deals with aircraft that fly into an electric field near a charged region. Aircraft can enhance the field to such an extent that streamers develop and eventually the charged region will be temporarily neutralized by a lightning strike. The NASA F-106B research airplane used during the NASA Storm Hazards Program recorded 714 direct strikes. The report indicates areas of the aircraft that enhance the field the most are sharp extremities, leading edges of wings, tops of the fuselage and engine inlets (8:n.p.). However, the data also showed the entire exterior surface is "susceptible to direct or swept lightning attachments" (8:n.p.).

The second concept offered by Clifford and Kasemir (5:119), concerns aircraft flying in clouds with a mixture of ice and water (mixed-phase precipitation). Since these are not necessarily storm clouds, the charge build-up is caused by triboelectric effects--interaction on the surface of the aircraft with the cloud particles.

According to Corbin:

> There are three ways in which static electrification of an aircraft can occur: (1) frictional charging, (2) engine charging, and (3) induction charging. If the charge accumulation is sufficient, a number of interference generating processes can occur. First, if the total aircraft is charged, electric fields at its extremities can become sufficient to cause corona-discharge breadkown of the air. Second, if insulated dielectric surfaces are charged, such as a windshield or a radome, a stream (spark-like discharge) can be initiated across the dielectric surface to surrounding metal structure. Third, if isolated (unbonded) metal sections of the aircraft become charged, sparkover to adjacent metal structure can occur. Finally, slowly varying induction pulses can be produced in antennas moving through clouds of charged particles. (6:322,323)

As well as the electromagnetic interference to internal systems caused by the static electrification that Corbin describes, an airplane with such a build-up of electrification has an increased potential to trigger a lightning strike. As pointed out by Fisher and others (8:n.p.), the former use of aluminum skins and mechanical control systems reduced the threat of lightning. However, the new composite materials being used for airplane and rocket skins and the increasing use of digital avionics and fly-by-wire systems have increased the risk of lightning and the damage done when lightning does strike. The composite materials tend to be dielectrics and do not readily dissipate the charges that build up. Digital avionics are easily upset by transient electrical currents as illustrated by AC-67.

Effects of Lightning on Airplanes and Rockets

The dangers of lightning to an aircraft are numerous and diverse since nearly any component can be affected by some attribute of lightning (heat, electrical current, electromagnetic impulse, brightness, etc.), and any part of the airplane may be struck (8:n.p.). A rocket may have the added hazard of leaving an ionized plume or conducting path behind it. There was evidence in AC-67 that the lightning followed the rocket exhaust plume back to the pad (31). Whether or not the ionized plume is really a factor is still being researched (35:51-52). Generally, though, a rocket will be susceptible to the same hazards as an airplane since it has many of the same components. Corbin listed the following six general categories of hazards and their causes (6:324).

HAZARD	CAUSE
Structural Damage	Direct Lightning Attachment
Fuel Tank Explosion	Spark Ignition of Fuel
Control System Malfunction	Direct/Induced Effects
Loss of Engine Power	Acoustic Shock
Release of External Stores	Direct/Induced Effects
Flash Blindness/Elec. Shock	Direct/Induced Effects

Each of these hazards can have minor consequences or conceivably cause the loss of the airplane. For example, structural damage can be as minor as a pin hole in the skin or as severe as the total destruction of the radome--and perhaps the airplane.

When a T-38A airplane was struck by lightning on 24 February, 1987, three of the above categories were demonstrated (9:360-361). Considerable structural damage was done to the airplane due to an explosion and the ensuing fire which destroyed most of the center fuselage section. The crew also experienced minor electrical shocks and saw a bright flash of light at the time of the strike. The crew landed with no injuries, but the potential consequences of a direct lightning attachment were demonstrated quite dramatically.

The potential effects of lightning on a space vehicle were demonstrated by Apollo 12 and the loss of AC-67.

When it was thought that lightning strikes were caused by intercepting naturally occurring strikes, the only way known to prevent lightning damage was to avoid lightning producing activity. However, one conclusion of the NASA Storm Hazards Program was that the majority of lightning strikes to aircraft are actually triggered by the airplane itself (8:n.p.). Therefore, simply avoiding natural lightning is not sufficient. Measures must also be taken to reduce the probability of triggering lightning.

Reducing the Probability of Triggering Lightning

The most obvious way to reduce the chances of triggering lightning is to avoid situations where lightning is a threat. While commercial aircraft experience about one lightning strike for each 3000 hours of flying time, military aircraft are only struck once for about each 30,000 hours of flying time (4:n.p.). This is partially due to the fact that commercial aircraft are more rigidly controlled in their routes. Military pilots are more frequently able to avoid undesirable weather without affecting schedules and flight plans.

Avoidance of triggered lightning for rockets takes the form of launch constraints. The loss of AC-67 prompted the development of a new set of lightning launch constraints. Colonel John Madura (Eastern Space and Missile Center Meteorologist) stated that the first edition of the new constraints was very conservative because "the scientific data base from which most constraints were derived is poor" (25:1). This conservative tone was the result of attempts to assure that the next launch would be absolutely safe. However, some in the operational community feared that launching would be nearly impossible with that set of constraints. After a series of iterations and revisions, a set of lightning launch constraints was approved in late March, 1988. In their present form, there must be "clear and convincing evidence the . . . constraints are not violated" (25:attachment).

History of Lightning Launch Constraints

Although two ways to reduce the threat of triggered lightning to aerospace systems have been identified, the intent of this thesis is to focus on the avoidance of the threat via launch constraints and launch commit criteria. A short history of the evolution of the constraints is presented; then, the current set of constraints is examined more closely.

Lightning launch constraints are not new to launch operations. However, they have changed significantly as more has been learned about lightning and its danger to vehicles. When Apollo 12 was launched in 1969, the only rule was that "the vehicle will not be launched when its flight path will carry it through a cumulonimbus (thunderstorm) cloud formation" (1:3). This was an easy rule to understand and could be verified by visual observation. However, as Apollo 12 demonstrated, this rule was not sufficient.

Following the Apollo 12 incident, the rules were revised to include restrictions on launching:

A. Within 5 statute miles of a cumulonimbus (thunderstorm) cloud or within 5 statute miles of an associated anvil.

B. Through cold-front or squall-line clouds which extend above 10,000 feet.

C. Through middle cloud layers 6000 feet or greater in depth where the freeze level is in the clouds.

D. Through cumulus clouds with tops at 10,000 feet or higher. (1:4)

These constraints are more restrictive, and focus on penetrating certain types of clouds as well as getting close to them. The standoff distance of 5 statute miles only applies to active thunderstorms or anvils. The constraints are still based on some easily and routinely observed meteorological parameters. Constraint B, though, is vague since it could also apply to cirrus clouds which precede cold fronts by as much as several hundred miles. Normally, these clouds would not be considered dangerous. Also, cloud layers and cloud tops are not routinely reported, and that data must be gathered on a specialized basis, e.g., with a dedicated aircraft that can fly through the clouds and measure their heights and thicknesses.

For the Apollo Soyuz Test Project (ASTP) in July, 1975, somewhat different constraints were used. There was a 3-mile standoff from anvils which is a slight relaxation of the first rule above, but flight through cumulus clouds with the freezing level in the clouds was not allowed. However, due to the criticality of the timing on ASTP (the Soviet space craft with which the Apollo was to rendezvous was already in orbit and launch windows were only a few minutes long), provisions were made for relaxing the constraints (7:4.30). If it could be shown by means of a ground-based electric field mill network or an airborne field mill that the atmosphere was electrically benign, the constraints could be relaxed at the discretion of the launch director (15:n.p.).

The original shuttle lightning launch commit criteria (LLCC) included the following:

> The space vehicle will not be launched if the nominal flight path will carry the vehicle:
>
> A. Through a cumulonimbus cloud except as noted in B.
>
> B. Within five (5) statute miles of a cumulonimbus (thunderstorm) cloud. An anvil many be penetrated if the approach is no closer that one core diameter from the core of the edge.
>
> C. Through or within five (5) miles of any other clouds where radar shows precipitation and the tops exceed the -10°C temperature altitude.
>
> D. Through decay clouds from local or distant active storms. This rule may be relaxed based on ground/airborne electric field measurements (TBD). (15:attachment 2)

"Following the AC-67 accident investigation, several groups proposed revised launch constraints to delete the risk of encountering natural or induced lightning" (26:1). Weather support to the Eastern Space and Missile Center (ESMC) at Cape Canaveral Air Force Station is provided by ESMC/WE of Detachment 11, Second Weather Squadron. The groups that proposed launch constraints were: Headquarters Space Division (SD/CLVT), The Western Space and Missile Center (WSMC), NASA Expendable Vehicles (NASA CV), and the Heritage Commission (independent study group sponsored by Space Division) (26:1). By November 1987, ESMC/WE had reviewed the proposed launch constraints and found they all contained "virtually the same generic limitations" (26:1). Therefore, they expressed a desire to "standardize launch constraints for Air Force ELVs, NASA ELVs, and NASA manned vehicles as much as possible" (26:1).

The proposed constraints went through a series of discussions and iterations and by late March 1988, NASA and the USAF approved the following set of lightning launch constraints. The USN approved them in August 1988.

NASA/USAF/USN

Lightning Launch Constraints

The Launch Weather Officer must have clear and convincing evidence the following constraints are not violated:

1. Do not launch if any type of lightning is detected within 10 nautical miles of the launch site or planned flight path within 30 minutes prior to launch, unless the meteorological conditions that produced the lightning have moved more than 10 nautical miles from the launch site or planned flight path.

2. Do not launch if the planned flight path will carry the vehicle:

a. Through cumulus clouds with tops higher than the $+5^{\circ}C$ level; or,

b. Through or within 5 nautical miles of cumulus clouds with tops higher than the $-10^{\circ}C$ level; or,

c. Through or within 10 nautical miles of cumulus clouds with tops higher than the $-20^{\circ}C$ level; or,

d. Through or within 10 nautical miles of the nearest edge of any cumulonimbus or thunderstorm cloud including its associated anvil.

3. Do not launch if, for ranges equipped with a surface electric field mill network, at any time during the 15 minutes prior to launch time, the one minute average of absolute electric field intensity at the ground exceeds 1 kilovolt per meter (1kv/m) within 5 nautical miles of the launch site unless:

a. There are no clouds within 10 nautical miles of the launch site; and,

b. Smoke or ground fog is clearly causing abnormal readings.

Note: For confirmed instrumentation failure, continue countdown.

4. Do not launch if the planned flight path is through a vertically continuous layer of clouds with an overall depth of 4,500 feet or greater where any part of the clouds are located between the zero (0) degree and the minus 20 (-20) degree celsius temperature levels.

5. Do not launch if the planned flight path is through any cloud types that extend to altitudes at or above the zero degree celsius level and that are associated with <u>disturbed</u> weather within 5 nautical miles of the flight path.

DEFINITION: Disturbed weather is any meteorological phenomenon producing moderate or greater precipitation.

6. Do not launch through thunderstorm debris clouds, or within 5 nautical miles of thunderstorm debris clouds not monitored by a field mill network or producing radar returns greater than or equal to 10dBZ.

DEFINITION: Debris cloud is any cloud layer, other than a thin fibrous layer, that has become detached from the parent cumulonimbus within 3 hours before launch.

GOOD SENSE RULE:
Even when constraints are not violated, if any other hazardous conditions exist, the Launch Weather Officer will report the threat to the Launch Director. The Launch Director may hold at any time based on the instability of the weather.

Comments on the Current Set of Lightning Launch Constraints

The new set of lightning launch constraints is unique in that the constraints are intended to be quite general in at least two ways. First, they were approved by NASA, the USAF and the USN as constraints for essentially all launch vehicles--shuttles as well as ELVs. The wording for earlier sets had evolved differently for various systems and although they were all similar in content, some ignored useful tools like the field mill network. A single set helps avoid confusion and misinterpretations. A second way that the constraints are general is that they should apply to all launch locations. The theory is that if a given set of meteorological parameters causes a lightning threat in Florida, the same set of parameters would indicate a threat in California, Oklahoma or Alaska. The real difference between the danger of lightning in Florida and California is simply how often certain conditions occur. Climatologically, there is more lightning in Florida than there is in California because the conditions are right for lightning in Florida more often than in California. These constraints are based on causal weather conditions, not climatology. Therefore, the constraints are transferrable.

A basic requirement of the constraints is that there must be "clear and convincing evidence the . . . constraints are not violated." This is an indication of the conservatism of the constraints. If, on any point, the launch weather officer is not SURE a constraint is not violated, then it must be assumed the constraint has not been met. This can be a very subjective area since "clear and convincing" cannot be quantified equally for every potential launch weather officer. "Clear and convincing" assumes certain meteorological equipment is available, and also centers on the launch team concept where any dissenter is heard and accepted (24).

The first numbered constraint speaks of ANY type of lightning within 10 nautical miles of the launch site or planned flight path within 30 minutes prior to launch. Figure 1 illustrates the 10 nautical mile standoff criteria. The 10 nautical mile standoff distance is based on measured distributions around parent storms. Jacobson and Krider showed in 1976 that nearly 80% of lightning strikes that hit the ground did so within 5 kilometers of the center of the storm (14:116). Nearly 100% occurred within 10 kilometers. A standoff distance of 10 nautical miles represents a safety margin of nearly 10 kilometers. "Any type of lightning" refers to in-cloud, cloud-to-cloud, cloud-to-air, and cloud-to-ground lightning. Although cloud-to-ground lightning is normally the most powerful lightning discharge, any lightning strike to the vehicle could be devastating. The dangerous electric fields associated with a storm are not restricted to the

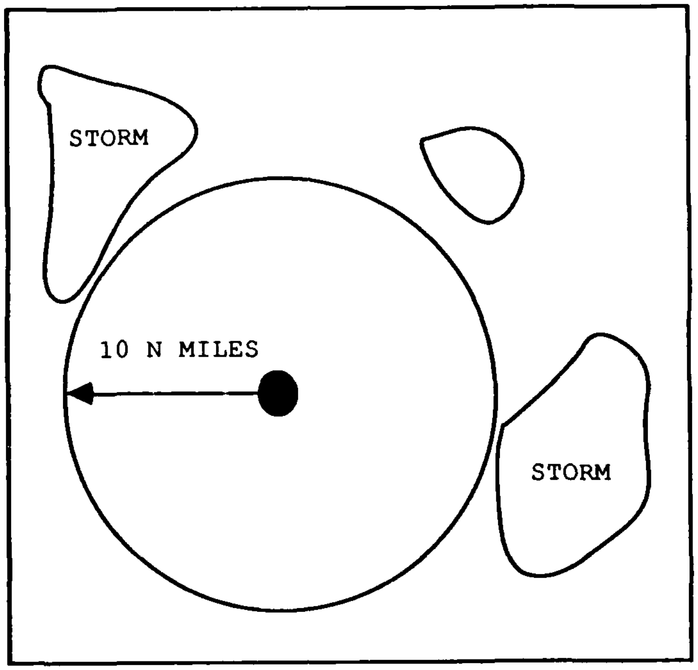

Fig 1a. Example of 10 N Mile Standoff from Launch Pad

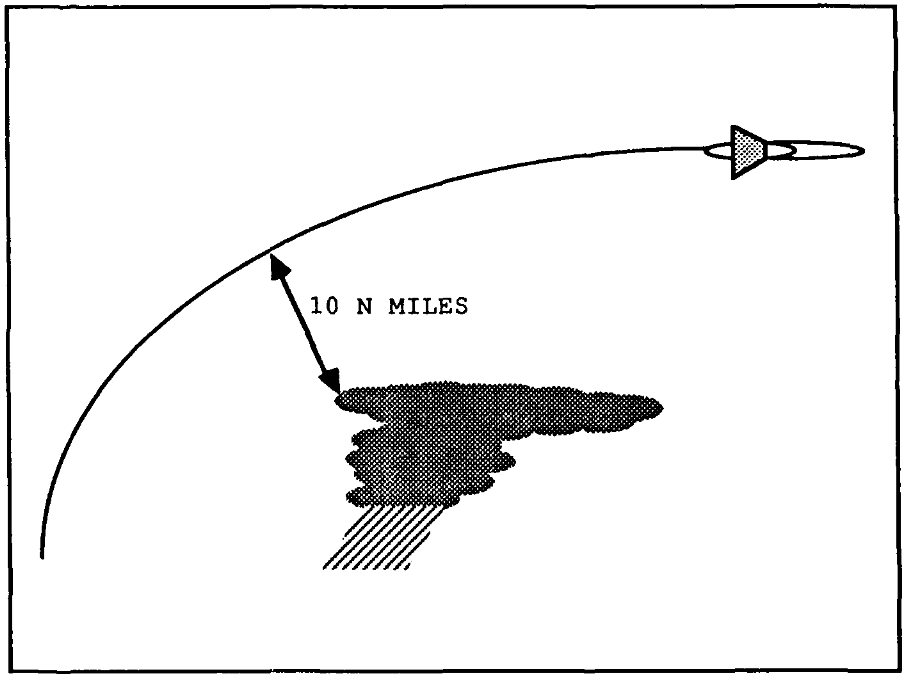

Fig 1b. Example of 10 N Mile Standoff from Flight Path

immediate vicinity of the discharge, nor do the fields dissipate completely after a discharge, or as the storm itself dissipates. However, if it can be shown that the "meteorological conditions that produced the lightning have moved more than 10 nautical miles from the launch site or planned flight path," the constraint will not be considered violated. ESMC/WE believes the field mill system at the CCAFS/KSC can give sufficient indication for when the E-fields have relaxed (returned to fair weather conditions) (26:attachment 2). For launch complexes without an electric field mill network this constraint will define a charge relaxation time.

Chapter 3 begins an analysis of this constraint based on actual lightning data, and a computer model is developed to further analyze this constraint in Chapter 4.

The second lightning launch constraint (illustrated by Figure 2) has four parts and addresses the flight path of the vehicle in connection with cumulus clouds. Cumulus clouds are singled out because they occur when there is convective activity and "convective activity correlates well to charge production, especially in terms of the upper level temperatures and height of the cloud" (24). Note: as the tops of the clouds get higher (colder), the standoff distances increase. See Figure 2a. During the summer in Central Florida, the 5°C level is around 12,000 feet, the -10°C level is around 21,000 feet, and the -20°C level is close to 26,000 feet. In winter, the levels are lower: 5°C occurs at about 8,000 feet, -10°C is near 16,000 feet and the -20°C level is near 21,000 feet (62:102,106).

There is some difficulty with arriving at an operational definition for "cumulonimbus" that is understood by meteorologists as

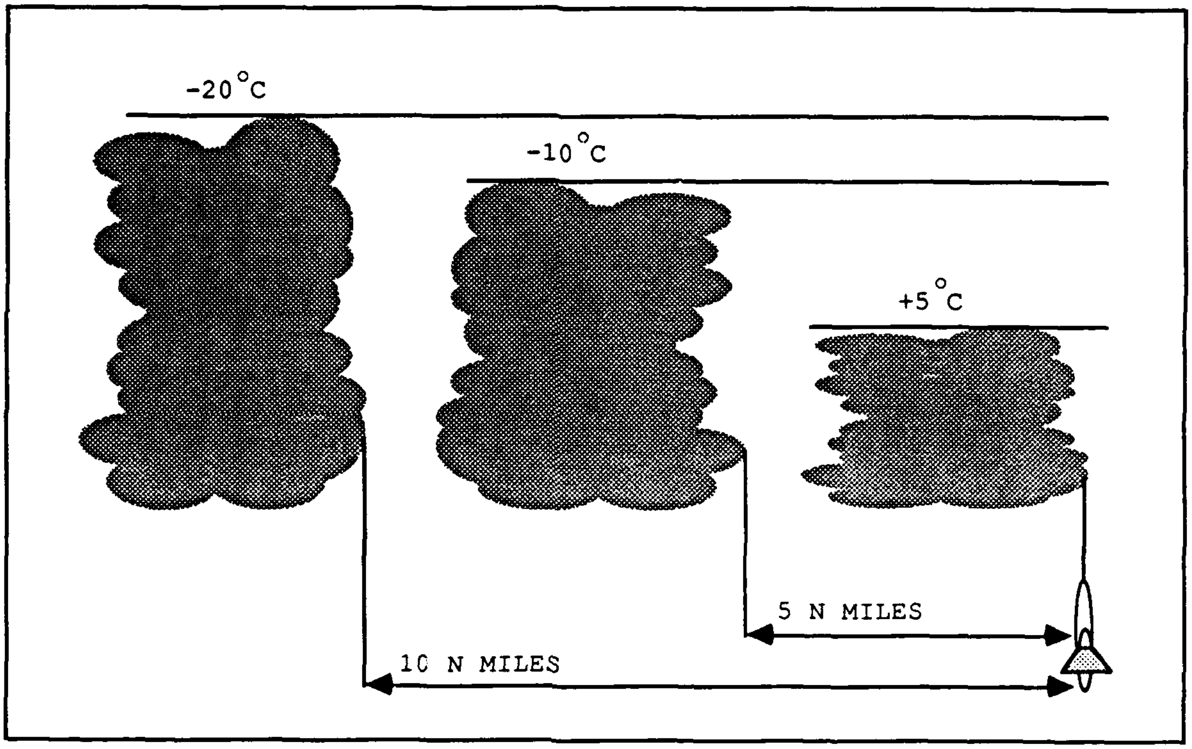

Fig 2a. Standoff Distances for Various Cloud Top Temperatures

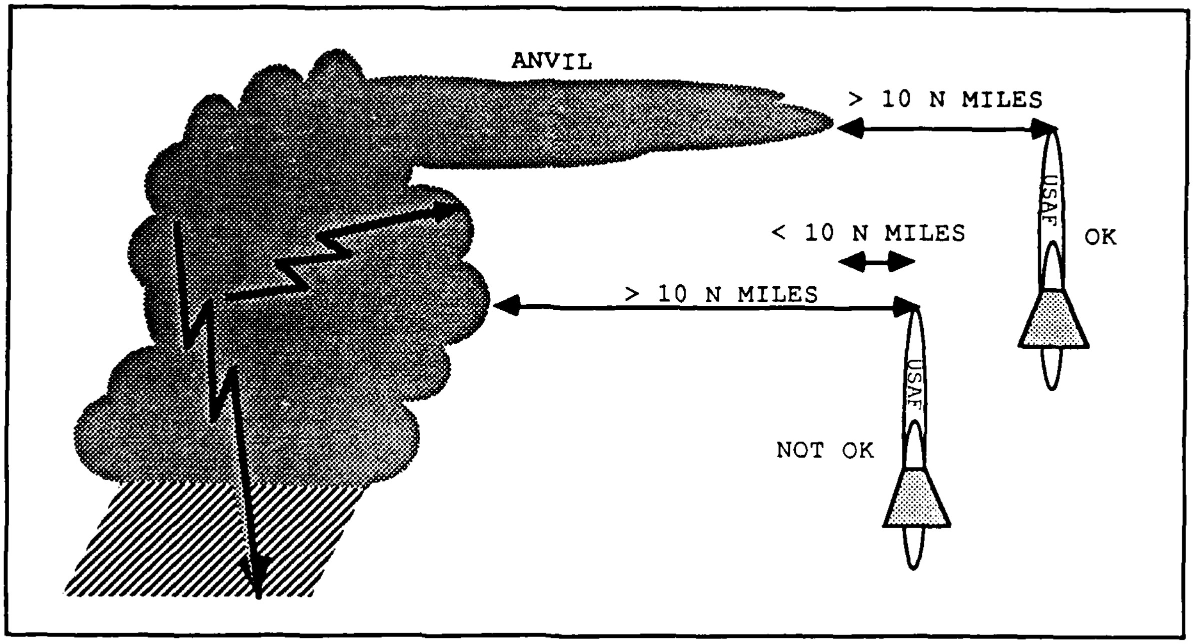

Fig 2b. Standoff Distances from Cumulonimbus and Anvils

well as mission management (26:attachment 2). Therefore, "cumulonimbus" and "thunderstorm" are both used in the fourth part of this constraint. Figure 2b illustrates the thunderstorm anvil and the standoff distance from it.

Tops of clouds can be difficult to determine and are not routinely reported by weather observers. There is no climatological data base with which to easily analyze this constraint for its potential impact on launch availability. (Satellite and radar data could be analyzed, but that would be a very difficult, time consuming and tedious task). Operationally, during a launch count, there are three obvious ways to determine cloud tops. First, if a meteorological sounding is made by launching an instrumented balloon through the cloud, the tops of the cloud can be inferred. This technique may be accurate enough, but it has some problems. First, it not technically feasible and does not allow for clear and convincing evidence. It would not be possible to launch a balloon into every cloud within 10 nautical miles of the flight path. Second, the balloon may rise through breaks in the clouds. Third, processing and collecting the data may take too long to make real time decisions.

A second possibility is satellite imagery. The temperature of the tops of clouds can be inferred from the cloud tops' infrared brightness. There are three primary problems associated with using satellite imagery: 1) Cumulus clouds may be too small in horizontal extent to be detected by the satellite. Visible resolution for geostationary meteorological satellites (satellites that maintain a constant longitudinal position over the equator) is at best one kilometer. However, visible imagery does not give any information on cloud temperatures. The best resolution with infrared imagery is four kilometers. 2) Unless rapid scan is available (new picture every five or six minutes), new pictures are available only once every 30 minutes. A convective cell may form and dissipate in 30 minutes. 3) The tops of cumulus clouds may be masked by a higher deck of cirrus clouds.

A third way to measure cloud tops is with an airplane that can actually fly through the areas of interest. In general, this is the most reliable method. If the weather is too bad for an airplane to fly, it is probably too bad to launch a space vehicle.

The third constraint deals with readings of an electric field mill network. Figure 3a shows the location of the field mills in the CCAFS/KSC Network. The field mills show the electric field intensity at the ground. Figure 3b is an example of contours of electric field intensity at ground level. Though the intensity at the ground is not equal to the intensity of the fields aloft, it is an indicator of fields aloft. This constraint calls for a 1 kilovolt per meter threshold. When AC-67 was launched, readings of more than 8 kilovolts per meter had been observed in the area (4:n.p.). However, at that time, a threshold had not been quantified, and field mill readings were not part of the constraints for the Atlas-Centaur Program.

Occasionally, smoke or ground fog can cause abnormally high readings of electric field mills. If it can be verified that smoke or ground fog is causing the high readings, and there are no clouds within 10 nautical miles, this constraint can be waived. Further characteristics of the electric field mills will be discussed in the next section of this chapter.

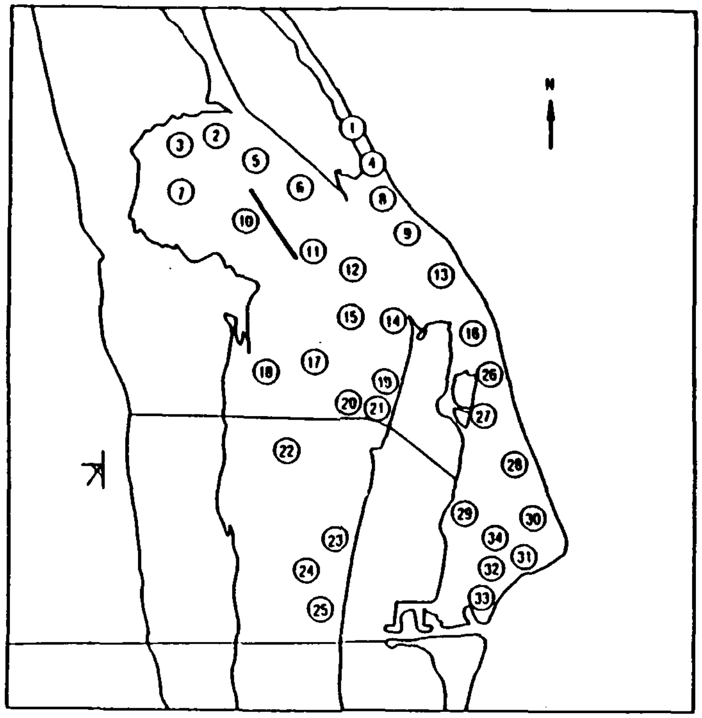

Fig 3a. Location of Field Mills in the CCAFS/KSC Network

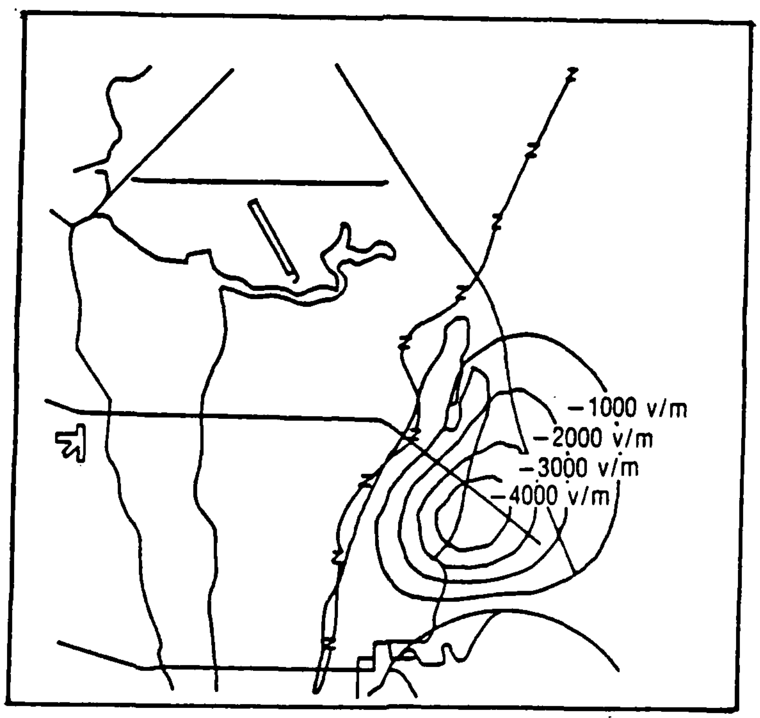

Fig 3b. Contours of the Electric Field at the Surface

The field mill constraint fills in some of the holes left by the first two constraints. The first constraint speaks only of lightning that has already occurred, whereas the field mills alert one to the potential of lightning to occur in the near future. The second constraint is based on the statistical correlation of high cloud tops and lightning potential. The field mills offer a measurement of at least the electric field strength at the ground. Since field mill data have not been routinely archived, a full analysis of this constraint is not yet possible.

The fourth constraint is based on empirical findings by Imyanitov, et al (13:7-12). Using airborne electric field mill measurements, they found even non-thunderstorm clouds could produce significant charges. Their findings were for clouds 5900 feet thick or greater, any part of which was between 0°C and -10°C if the clouds contained ice and supercooled water (liquid water colder than 0°C). This constraint restricts launching through layered clouds that are greater than or equal to 4500 feet thick if any part of the clouds are between 0°C and -20°C. The 4500 feet reflects the lower latitude of the United States launch sites and a significant margin of safety (24). Figure 4 illustrates conditions when launching would and would not be permitted.

The layered cloud constraint (Constraint Number 4) covers situations where the electric fields aloft may be masked from the ground-based field mill network by space charge, and where natural lightning is not occurring, thus it is not seen by human observers or other lightning detection techniques. Essentially, this constraint attempts to alert mission personnel there is a potential for triggered lightning, even if no natural lightning is occurring.

This constraint has no direct data base associated with it from the Cape area. It is possible to infer the tops and bases of clouds, and the temperatures at which they occur, from standard meteorological soundings; however, those soundings are taken only every 12 hours at most, and even less frequently at the Cape. Even if tops and bases could be inferred, that would only indicate a frequency of occurrence. The electric fields in those clouds would also be needed. Building a data base to analyze this constraint will require more frequent observations to ensure proper sampling.

The fifth constraint deals with launching through clouds that extend to or above the 0°C level and are associated with disturbed weather within 5 nautical miles of the flight path. Figure 5 illustrates this constraint. Disturbed weather is defined as any meteorological condition producing moderate or greater precipitation. Moderate precipitation registers about 30dBz on radar and measures about 12.5 millimeters of precipitation per hour. The precipitation can be monitored by radar. This is not necessarily a summertime constraint since frontal activity can bring moderate precipitation in the winter--and in the winter the 0°C level may easily be below 1000 feet. This constraint is based on the previously mentioned front/squall line rule. (See the rules developed following the Apollo 12 incident, listed earlier in this chapter). Clouds that have their origin in fronts or squalls may be charged and may maintain that charge.

The final constraint prohibits launching within 5 nautical miles of thunderstorm debris clouds. These are the clouds that have become detached from the parent cumulonimbus within the past three hours or

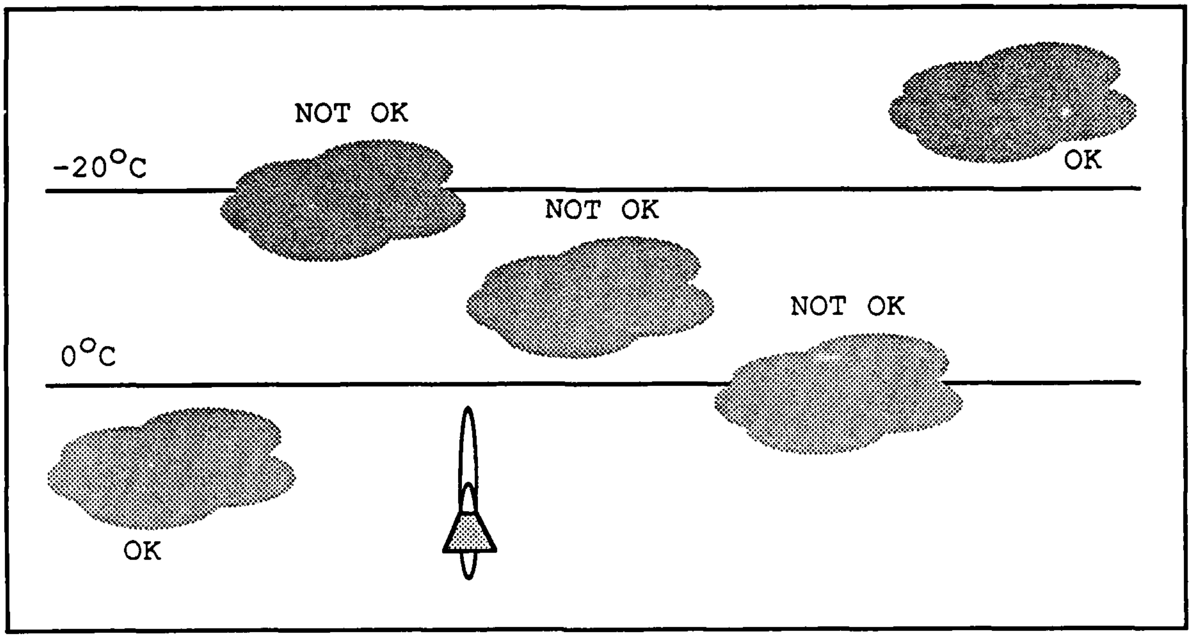

Fig 4. Conditions Where Launching Would and Would Not be Permitted Through a 4500 ft Deck of Clouds.

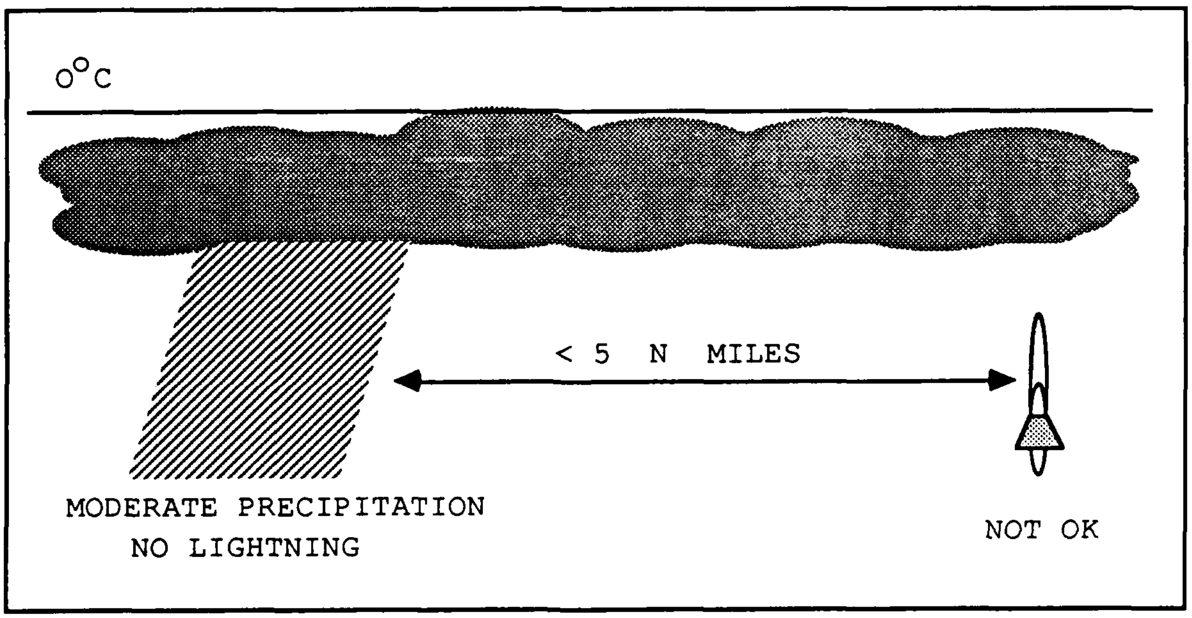

Fig 5. Illustration of Constratint #5--Launching Through Clouds Associated with Moderate Precipitation/No Lightning

clouds that persist after the organized thunderstorm dissipates. Even after a storm dissipates, or when clouds become separated from the parent storm, pockets of charge persist. These pockets of charge pose a threat of triggered lightning to launch vehicles. Precise times required for the fields of a given storm to relax are not known. Estimates between 20 minutes and 60 minutes have been suggested. The three hour period provides a safety margin (3). According to the constraint, if the clouds are not producing precipitation which registers greater than or equal to 10dBz (light rain), and the fields can be monitored by a field mill system and are found to have relaxed, the standoff distance is relaxed from "5 nautical miles" to "through."

The occurrence and durations of thunderstorm debris clouds are not routinely observed and recorded. Thus, insufficient data prevents analysis of this constraint.

The "Good Sense Rule" is a catch all--just in case conditions exist that could not be anticipated by the constraints but would threaten the safety of the launch. It also allows the meteorologist to use current technological breakthroughs before the constraints can be changed.

Observing the Parameters that Indicate a Threat of Triggered Lightning

Due to the complexities of the launch constraints, more and more sophisticated equipment is needed just to observe the necessary parameters. Along with surface based observations, a variety of equipment is available to observe lightning activity and consequently help forecast the potential for lightning. Lockwood describes most of this equipment in the "Cape Canaveral Forecast Facility Equipment

Operations Notebook" (19:1-79). This portion of the report briefly describes that equipment. The output of all of the systems described here is available in near-real-time to the forecasters, launch weather officers, and launch officials at the Cape Canaveral Forecast Facility (CCFF) and the Range Control Center. Note that in addition to direct observation of lightning, the weather staff must monitor and consider other meteorological factors which impact launch activity. For example, surface and upper level winds are a concern due to their effect on the flight and structural loading of the rocket. Surface winds are also important in the event of leakage of corrosives or poisonous gasses, since these gasses could be dispersed into work areas or populated areas off range. Convergence of surface winds is also an important indicator of potential convective activity that may produce lightning (20:1-42). Integration and display of this massive quantity of information are very important.

The volumetric scan radar has only become fully operational in the past year. This is a WSR-74C 5-centimeter wavelength weather radar located at Patrick Air Force Base (about 20 miles south of CCAFS) and was selected for its higher sensitivity (relative to a 10-centimeter wavelength weather radar) for smaller hydrometeors, e.g., mist or drizzle, which can have an adverse impact on vehicles such as the Shuttle. In addition to the normal 360 degree azimuth scan, the radar antenna automatically shifts through 24 different angles above the horizon to provide a three-dimensional view of the area. The radar completes its composite scan in about 5 minutes. The data is then digitized and can be displayed in numerous different forms for the weather staff. Naturally, this is a very important piece of equipment for monitoring the location, growth and extent of cells and thunderstorms. Radar data can also be used to detect the "disturbed weather" of Constraint Number 5 and "10dBZ radar returns" of the sixth constraint. Since the volumetric scan radar is relatively new, its data base archive is too limited to produce an analysis of the new lightning launch constraints. This radar was being modified for volumetric scan and thus was not operational when AC-67 was launched.

In addition to the radar at Patrick, the CCFF receives the National Weather Service (NWS) radar scan from Daytona Beach, FL. Other radar images (for example, Miami or Galveston) can also be dialed up via modem if needed. The NWS archives the scan images in both digital format as well as 16 millimeter movie film loops, and they are useful for analyses (12:1-9; 23:1-16). However, these data sets are very large data sets (250 6250-BPI tapes per year) and processing would be a non-trivial task that could take several years.

The Weather Information Network Display System (WINDS) is, appropriately enough, a system to measure the winds and temperatures around the Cape. WINDS is a system of 16 permanent instrumented towers which measure the winds and temperatures from the surface up to 500 feet across CCAFS/KSC. These data are used to supplement the overall meteorological picture and assist in producing the best possible forecast. Though not itemized in any lightning constraint, the winds can be an important factor to the forecaster concerned about lightning. Even though a lightning producing system has moved out of the area, converging winds may indicate that more convective activity is imminent. There is a relationship between lightning and low-level winds that cannot be overlooked. Lopez and Holle describe the dependency of thunderstorms on low-level winds (up to 10,000 feet) in Central Florida (20:1-42).

One of the most useful systems currently available to forecast potential lightning and triggered lightning is the Launch Pad Lightning Warning System (LPLWS). This is a network of electric field mills which measure the ambient electrostatic field directly overhead. Figure 3a shows the location of the field mills around the Cape. The first field mill was set up at the Cape in 1967 for a Polaris study. It was not until 1969 when Apollo 12 was struck by lightning that a full network was planned. The network was not finished until 1981, and became fully range certified (accepted as an operational tool) in February 1988. Currently, the system is being upgraded to make it more accurate, less noisy, and easier to calibrate. Though this system was in use, and constraints had been established for it in connection with space shuttle launches, no constraints were in effect at the Eastern Test Range for LPLWS readings during ELV launches when AC-67 was struck by lightning. The Atlas-Centaur accident brought new awareness to the importance of a field mill network to the launch community.

There are three basic applications for the LPLWS. The simplest application is to determine the presence of electrical charge in the clouds. When the field readings are large, there is usually a hazardous electrical charge nearby. When large, abrupt jumps are recorded, lightning discharges are being produced. A second application is to map where the charge build-up is and to locate where lightning (cloud-to-cloud and cloud-to-ground) is occurring. The electric field is contoured to show the center of the charge build up. See Figure 3b. This may not provide adequate information to deduce the field aloft, but it can be used in conjunction with other data sources (radar, LLP, aircraft reports) to good advantage. A third use for the network is to analyze the amount of cloud charge which is being neutralized by a lightning discharge and where this charge was located in the cloud. All of these applications are used by the meteorologist to better understand the lightning hazard. The LPLWS is useful in helping evaluate the first lightning launch constraint, and as such, data derived from this system is used in chapter 4 to help develop a lightning model.

The Lightning Location and Protection, Inc. (LLP) system has the ability to detect and locate cloud-to-ground lightning strokes. It does this with orthogonal loop direction finder (DF) antennae. (Appendix A provides more details on the LLP network theory and operation). There are two systems at the Cape--a low gain and a medium gain system. The low gain system uses two DFs and can detect either positive or negative cloud-to-ground strokes from 10 to 100 kilometers away with a location accuracy of 0.5 kilometers, and is particularly useful to monitor activity around the launch pads on the Cape. See Figure 6 for the location of several pads. The medium gain system employs three DFs and is designed to detect only lightning that lowers negative charge to the ground--hence it does not discern positive flashes. This system can detect lightning out to 400 kilometers with an accuracy 0.5 to 1 kilometer. Figure 7 for shows an example of the output from the medium gain system. The LLP system is most useful to verify location of lightning for the first constraint.

LLP data has been collected and saved for several years and output from the medium gain system is used in Chapter 3. Unfortunately, only

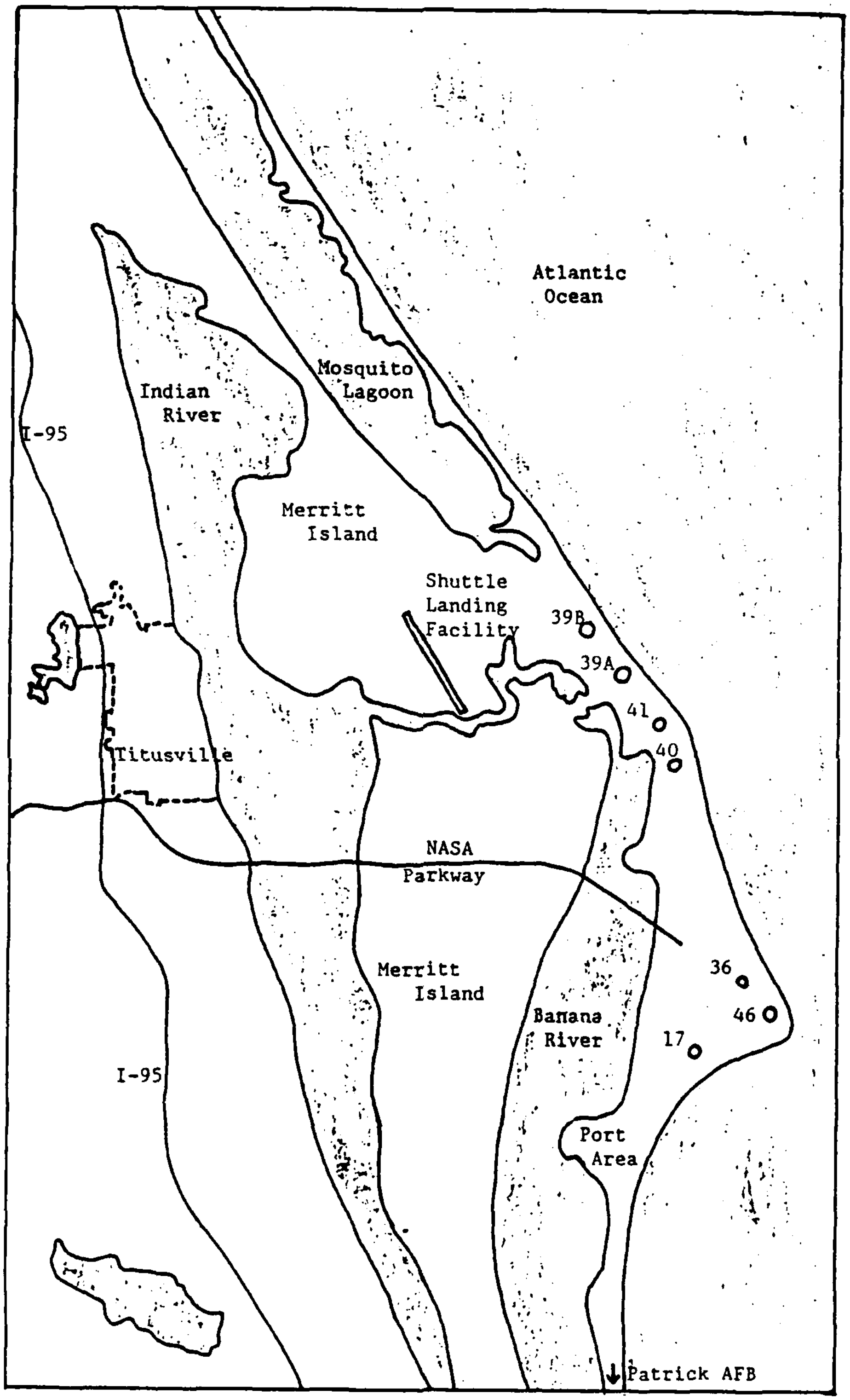

Fig 6. Map of the Cape Canaveral and Kennedy Space Center Area

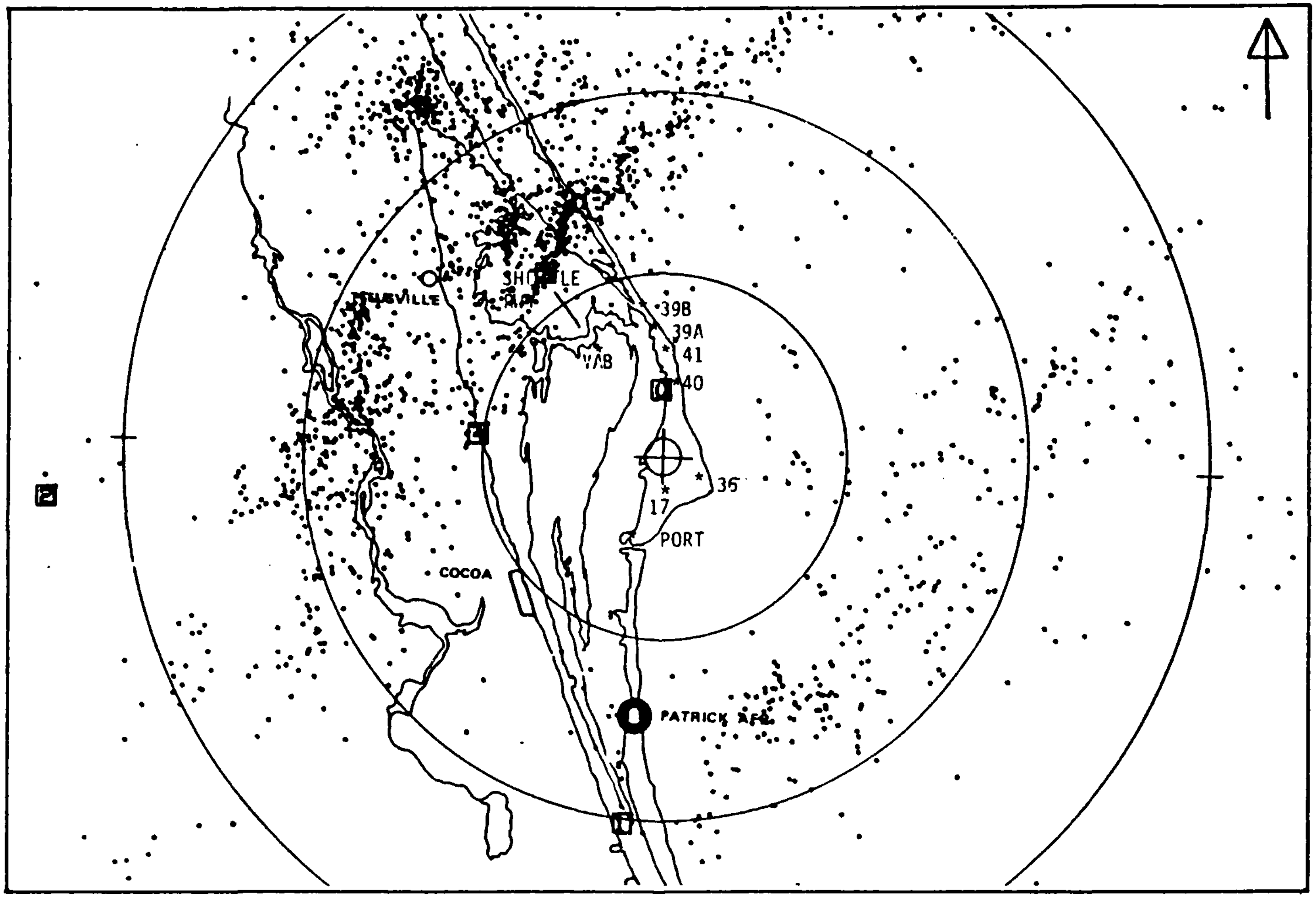

Fig 7. Example of LLP Output

(Figure Supplied by Det 11, 2WS)

2 years of the data are currently in a usable form and there are gaps in the data due to equipment downtime.

This report has already alluded to the complexity of receiving, analyzing, interpreting, and briefing this mass of data during a launch count. The Meteorological Interactive Data Display System (MIDDS) assists considerably in assimilating the data in formats and analyses usable by the launch team. The MIDDS is a dedicated system installed on an IBM 4381 computer. It has some unique capabilities which are described. Geostationary Orbiting Environmental Satellite (GOES) data are available on the MIDDS every 30 minutes. These digital images are displayed on a high-resolution monitor. (A latitude band from about 70N to 70S is available, but only a portion of the band is normally used for launch operations). The most recent satellite picture is never more than about 36 minutes old. For example, the 0600 satellite picture is normally ready to view by 0606, and the 0630 picture would be available at 0636. (Rapid Scan makes pictures of a smaller latitude band available every 5 minutes. This can be used during launches, if needed). Visible imagery (resolutions of 1 and 4 kilometers at the equator) is available every 30 minutes during daylight hours, and infrared imagery (4 kilometer resolution at the equator) is available every 30 minutes from both the Eastern and Western GOES. When these pictures are received by the MIDDS, they overwrite the oldest picture, but typically 6 hours are saved, making "satellite loops" possible. These loops are extremely useful in observing and forecasting storm activity and movement. The satellite data can be used (under the right conditions) to help verify each of the 6 constraints.

The MIDDS is also an excellent data manipulator. Observed and forecast data from the CCAFS sensors, as well as data from across North America are continually being fed into the computer which sorts and saves the data, typically, for up to 6 days. In addition to the satellite imagery, it can overlay map outlines, data from the volumetric scan radar, lightning strike data, wind data, upper air data and derived meteorological parameters. It can do this all at once or display any selected aspect which the weather staff programs. This enables the forecaster to produce and correlate a 3-dimensional picture of the meteorological conditions which prevail, and allows the decision makers excellent visual presentations to make their decisions.

In addition to the preceding methods of observing the weather, there are two other techniques which should be mentioned. First, soundings of the atmosphere are vertical cross sections of the atmosphere which give information about the temperature, moisture and winds. These soundings are taken by launching an instrumented balloon and provide information such as the height of the +5°C, -10°C, and -20°C levels. The second technique that is valuable is the airborne observer. This observer can actually see the bases and tops of clouds and measure the temperatures at these critical places. He can also fly in the immediate vicinity of where the rocket will actually fly.

The systems mentioned above, and the constraints that they can help verify are summarized in Table 1.

Although the CCFF is the best equipped forecast facility in the Department of Defense, it is not perfect. For all launches, the threat of triggered lightning close to the launch pad may be well known, but, once launched in a down range trajectory over the Atlantic, the launch

Table 1. Summary of Methods Used to Observe the Weather Around Cape Canaveral, the Parameters They Measure, and the Constraints Which They Help Evaluate

Method of Observation	Parameter(s) Observed	Constraints
Ground-based Observer	Wind, Temp, Moisture Clouds, Lightning	1,5,6
WINDS	Winds, temperatures	1
RADAR	Precip, Cloud Tops	1,2,5,6
MIDDS (Satellite Data)	Clouds (Displays data from Other Sources)	1,2,3,4,5,6
LPLWS	Surface Electric Field	1,3,6
LLP	Neg Cloud-to-Ground Lightning	1
Soundings	Temp, Moisture, Winds	2,4,5
Airborne Observer	Cloud Layers, Temps	2,4,5

vehicle enters a data sparse region not covered by the field mill system. For the portion of the flight where lightning is considered to be a threat (up to 100,000 feet in altitude) measurements or determinations of the potential threat of triggered lightning must be made. This threat is a function of the electric field charge in the atmosphere. It is not known that the presence of an electric field can always be inferred by the presence of certain types of clouds. After all, it is the discharge of the electric field and not the cloud which is dangerous. Therefore, other measurements along the flight path over the ocean are needed.

In response to the dilemma of ascertaining actual charge as opposed to finding what are perceived to be symptoms of electric fields, it has been suggested that <u>in situ</u> measurements of the electric field be made. Since the field mills provide relatively good data for the ambient electric field, atmospheric scientists have suggested field mills be calibrated and flown on an aircraft in the vicinity of the rocket's proposed trajectory. If augmented with ground based field mill data, they propose this as one of the best ways to accurately determine the charge aloft. Field mills have been flown on aircraft for at least 30 years for research purposes (39), but are not currently being used in the operational arena.

Though an airborne field mill seems to be the ideal choice for taking in situ measurements, there are other ways to obtain the data. A small rocket with electric field sensing instruments could be launched along the projected path of the launch vehicle. This form of measurement has the advantage that it measures a high percentage of the launch vehicle's trajectory within minutes of launching the actual payload. Such rockets have been used before; however, none of them are currently available (39). Another method of measurement is a balloon which can carry instruments to accurately measure the field (29:303). This form of measurement is quite slow, however, and the balloon has the disadvantage of being carried by the winds to areas which may be far removed from the planned flight trajectory of the rocket. A third possibility is to carry dropsondes via aircraft to the area of interest and drop them through the clouds. These could be dropped through thunderstorm anvils and the associated cirrus blow off to determine the potential charge. Each of these techniques has advantages and disadvantages which need to be explored more fully. Perhaps, some combination of airborne field mills, rockets, balloons, and dropsondes would be the preferred method as opposed to relying totally on one system.

Cape Canaveral Climatology

The Cape Canaveral area is composed of two narrow strips of land on the east coast of Florida. See Figure 6. The Atlantic Ocean is on the East and the Indian River is on the West. The Banana River separates the Cape into two general areas: KSC on the West side and CCAFS to the East. At a latitude of 28.5 degrees North, the Cape is in the subtropics and is characterized by air mass thunderstorm activity in the summer and frontal activity in the winter. Associated with the air mass regime are frequent afternoon thunderstorms that can build up and dissipate in a time span of 60 minutes. Lightning is therefore a constant concern during the summer, affecting not only launch operations, but pad operations as well. During the winter, there tends to be less convective activity, but frontal passages can bring storms and charged clouds into the area. Such was the case for AC-67.

Temperatures at the Cape are rarely below 32 degrees Fahrenheit, but during clear, calm winter nights, or during windy periods of strong cold air advection, the temperature can easily drop below freezing on the Cape--as it did on 28 January 1986 when the space shuttle Challenger was launched. See Table 2 for more details on this and other aspects of the area climatology.

Surface and upper level winds are a concern for launch operations, particularly during frontal passages and when the jet stream is over Florida, but these criteria are fairly well defined and will not be further addressed by this report.

The greatest concern pertaining to launch operations is the prevalence of thunderstorms and their associated electrical charge. Table 2 shows that KSC records an average of 76 thunderstorms days per

Table 2. Selected Climatology for Kennedy Space Center

Mon	Temperatures Mean Max	Mean Min	Mean Ave	Extremes Max	Extremes Min	Thunderstorm Days	Winds Dir	Speed (kts) Ave	Speed (kts) Max
Jan	69	52	60	84	26	1	NNW	7	46
Feb	69	51	60	87	25	2	N	7	60
Mar	74	57	65	89	29	3	SSE	7	48
Apr	78	62	70	94	34	3	E	8	53
May	82	67	75	95	44	8	E	7	46
Jun	86	72	79	98	57	13	E	6	50
Jul	88	73	81	96	60	16	S	5	50
Aug	87	73	81	96	65	14	E	5	60
Sep	86	73	80	94	59	10	E	5	68
Oct	81	68	75	91	40	4	E	7	38
Nov	75	60	68	87	31	1	N	6	46
Dec	70	53	62	85	25	1	NW	7	41
Ann	79	63	71	98	25	76	E	6	41

(Adapted from 40:4.21)

year. The preponderance of those storms occur in summer with a peak in July. It is possible to have more than one thunderstorm on a given day. Piepgrass and Krider recorded 79 storms at KSC on 62 thunderstorm days (36:11196,11197).

There is a unique spatial distribution of lightning in the CCAFS/KSC area due to the land/water interfaces and other factors. The spatial distribution in the immediate vicinity of the Cape is examined in Chapters 3 and 5 of this report. Lopez and Holle show the spatial distribution for most of Central Florida in their 1987 report (21:1299-1311). The nature of the storms that produce this lightning is described in more detail in Chapter 4 where a model is developed to simulate Florida lightning activity.

III. Analysis of Cloud-to-Ground Lightning Data

Introduction

The lightning launch constraints were developed and designed to cover conditions in which lightning or triggered lightning would be a threat to space flight. As such, they all work together and cannot ensure adequate protection unless they are used as a whole. Similarly, an analysis of less than the whole set of constraints cannot give a complete picture of the impact the new constraints may have on launch availability.

Unfortunately, data do not exist with which to analyze most of the constraints. As Chapter 2 pointed out, each of the constraints needs observational input which has not been archived. However, the first constraint, which is concerned with natural lightning events, is partially verified with the help of the LLP network. This network has been providing data which has been collected for several years. Holle, Lopez, and Watson of NOAA's Environmental Research Laboratory (ERL) in Boulder, Colorado, have worked hard to put this data into a usable form and graciously agreed it could be used for this thesis. So far, ERL has completed work on two years of data--1983 and 1984. Those two years of data form the basis of the analysis in this chapter.

The first lightning launch constraint forbids launching when any type of lightning has been detected within 10 nautical miles of the launch site or planned flight path within the past 30 minutes. The 30 minute delay can be waived if the storm has clearly moved out beyond 10 nautical miles. The LLP network shows where and when most negative cloud-to-ground lightning occurs. An analysis of the LLP data for 1983 and 1984, then, can approximate the distributions of lightning in the CCAFS/KSC area and the impact of lightning on launch availability. This chapter performs a preliminary analysis of the first lightning launch constraints and develops a first order analysis of the nature of lightning activity in Central Florida.

Scope

The analysis in this chapter is strictly from a set of LLP data, and addresses the following topics:

1. The spatial and diurnal characteristics of lightning in the CCAFS/KSC area.

2. Launch availability for the summers (April through September) of 1983 and 1984 given the 10 nautical mile/30 minute launch constraint.

3. The effect on launch availability if the delay time and/or standoff distance from the launch pad were different.

This analysis considers only lightning with respect to the launch pad. Though the constraints also restrict launching when the flight path of the vehicle will come within 10 nautical miles of lightning activity (see Figure 1), this analysis does not consider the impact of lightning within the specified range of the flight path.

Assumptions

This portion of the thesis is based on the best data set currently available. Since the data set has some limitations, I made the following assumptions:

1. The geographic positions of the lightning flashes that were supplied with the data are correct. In reality, as mentioned in Appendix A, LLP data has some error associated with its location (10:n.p.; 30:n.p.). Lopez, et al, analyzed the coordinates extensively for their previous work with the data (21:1289; 20:3), and those coordinates will be used here.

2. These data are representative of the diurnal nature of thunderstorm (and lightning) activity in Central Florida.

3. This data set approximates the actual flash density (flashes per area) in the CCAFS/KSC area.

4. Launch availabilities calculated from these data are optimistic since the LLP network observes only about 80% of negative cloud-to-ground lightning. There were also periods of time when the network was not operational (downtime). I ignored the downtime since the exact hours for which the network was down are not available.

Since only two years of data were available, I did not assume these data are representative of the annual distribution of lightning. Furthermore, if indeed "normal" years do exist, meteorologists would have trouble calling either 1983 or 1984 "normal" since 1983 was influenced by a very strong El Niño (16:940), and 1984 was a transition period back to something perhaps more normal. The 1982/1983 El Niño affected placement of the jet stream and caused "abnormal" weather on a global scale--including the Florida area.

Characteristics of the Data Set

This section gives some preliminary statistics on the data set. The USAF Environmental Technical Applications Center (USAFETAC) provided the data. These were the general characteristics of the data when they were received:

Period of Record:	1983, 1984
Center Point:	Complex 40 28.56N (Latitude) 80.58W (Longitude)
Range of Data	100 Kilometers (KM) from Complex 40
Number of Flashes:	120,858
Parameters Included:	Year* Julian Day* Julian Minute* Hour* Minute* Second* X-Coordinate (KM from Daytona Beach) Y-Coordinate (KM from Daytona Beach) Flash Intensity Number of Return Strokes Y-Distance (KM from Complex 40)* X-Distance (KM from Complex 40)* Hour of Eastern Standard Time (EST)

The file required 17 megabytes of disk space. The starred (*) parameters define the flash completely for the purposes of this thesis; therefore, I made the following changes to the original file to create a working data file:

1. Calculated the month of the year, the latitude and longitude from the available data and added them to the file.

2. Deleted the unstarred items.

3. Deleted unnecessary spaces between the fields.

4. Changed all times from Greenwich Mean Time to Eastern Standard Time.

These changes reduced the working data file to 7 megabytes of disk space. The following is a sample of the working file.

YY	M	JD	JM	HH	MM	SS	LAT	LON	Y	X
83	2	41	58441	14	0	33	28.224	81.383	-37.6	-78.7
83	2	41	58441	14	0	34	28.754	80.269	21.4	30.1
83	2	41	58451	14	11	20	28.512	80.238	-5.6	33.1

where, for the first record:

YY	=	Year	=	1983
M	=	Month	=	2 (February)
JD	=	Julian Day	=	41st day of the year
JM	=	Julian Minute	=	58441st minute of the year
HH	=	Hour of Day	=	14 (2 p.m.)
MM	=	Minute	=	00 (2:00 p.m.)
SS	=	Second	=	33 (2:00:33 p.m.)
LAT	=	Latitude	=	28.224 Degrees North
LON	=	Longitude	=	81.383 Degrees West
Y	=	Y-Distance	=	-37.6 (37.6 KM West of Complex 40)
X	=	X-Distance	=	-78.7 (78.7 KM South of Complex 40)

The following graphs (Figures 8 to 15) show some more characteristics of the data. Figures 8 through 11 summarize all 120,858 flashes which were recorded within 100 kilometers of Complex 40. Figure 8 shows the annual distribution of the lightning. There are significant differences in the distributions for each year which will play a role in later parts of this analysis. For example, February, March, and April were active in 1983, but very quiet in 1984. In 1983, May was quiet, but in 1984, only July and August had more lightning activity than May. Overall, based on this data, 1983 was a much more active year than 1984 in Central Florida. Climatologically, July has more thunderstorm days, but August had more cloud-to-ground flashes during both years.

Figure 9 shows the diurnal distribution of lightning. Clearly, most summertime lightning in Central Florida occurs in the afternoon (between 1:00 and 6:00 p.m), as would be expected. Air mass thunderstorms build up in the afternoon when the land has been heated by the sun, causing a sea breeze. The sea breeze converges with prevailing westerly winds. That is the mechanism that triggers many air mass thunderstorms.

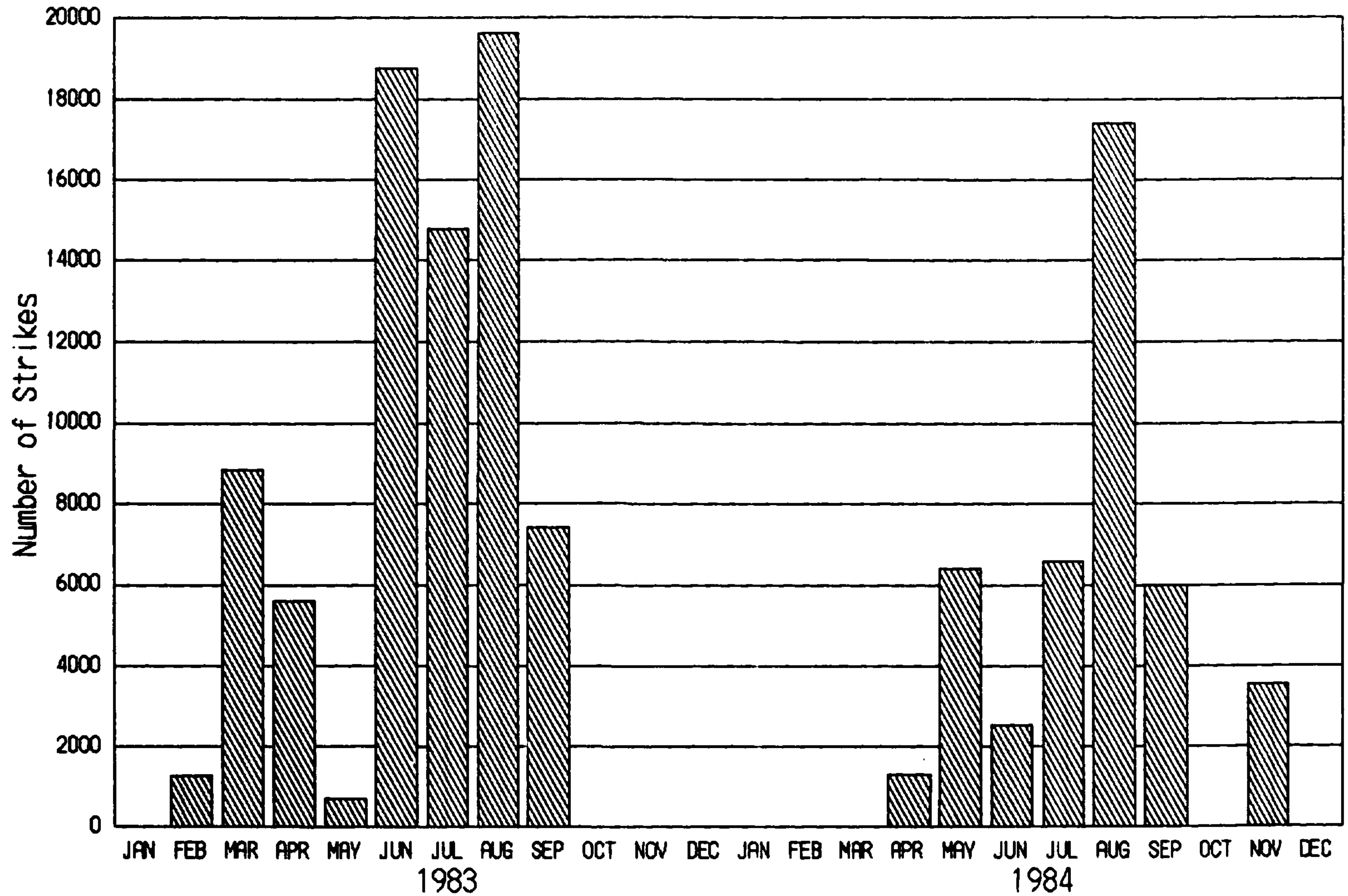

Fig 8. Lightning Strikes Detected by LLP During Each Month Within 100 KM of Complex 40

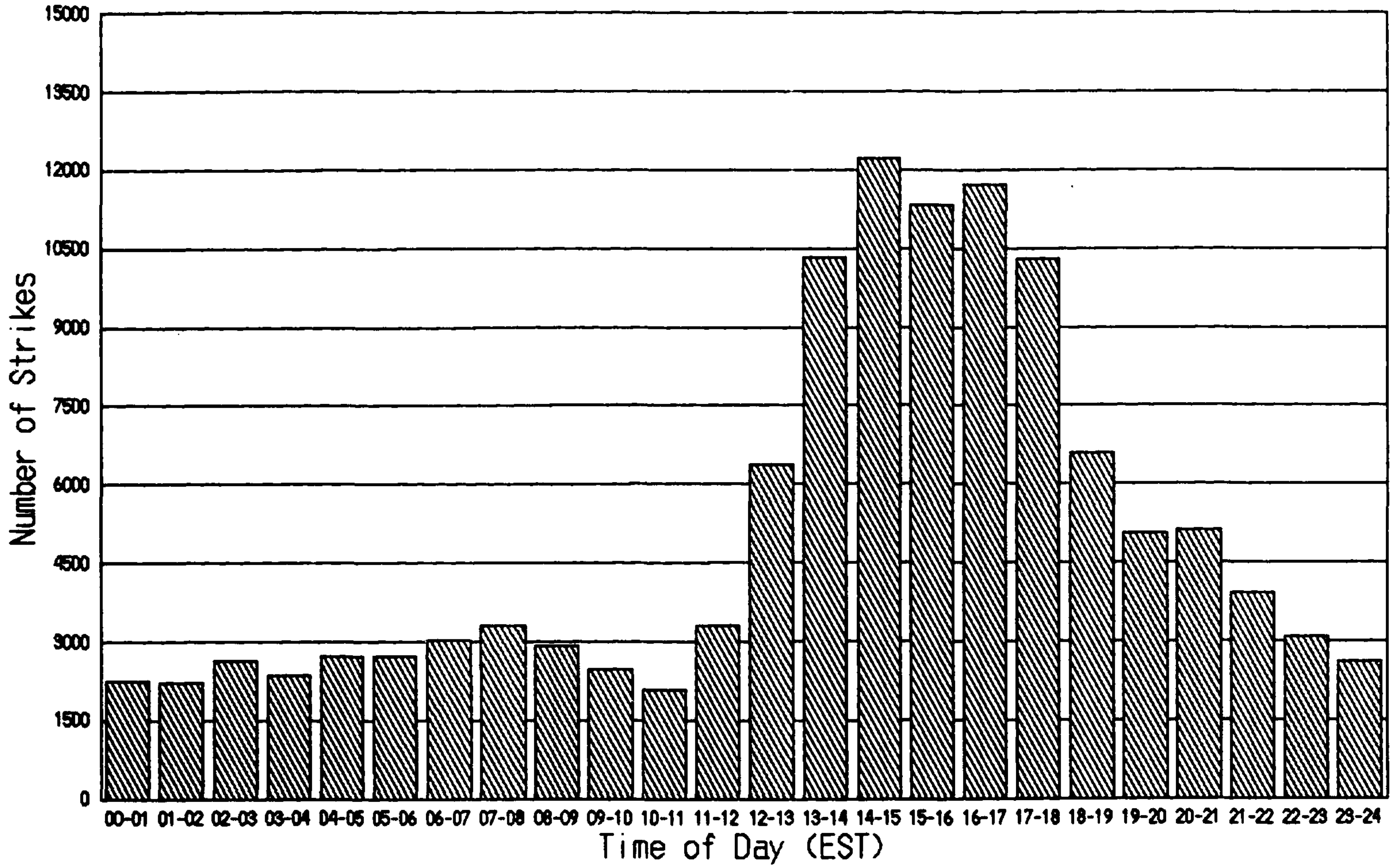

Fig 9. Lightning Strikes Detected by LLP Within 100 KM of Complex 40 During Each Hour of the Day
(Data Recorded in 1983 and 1984)

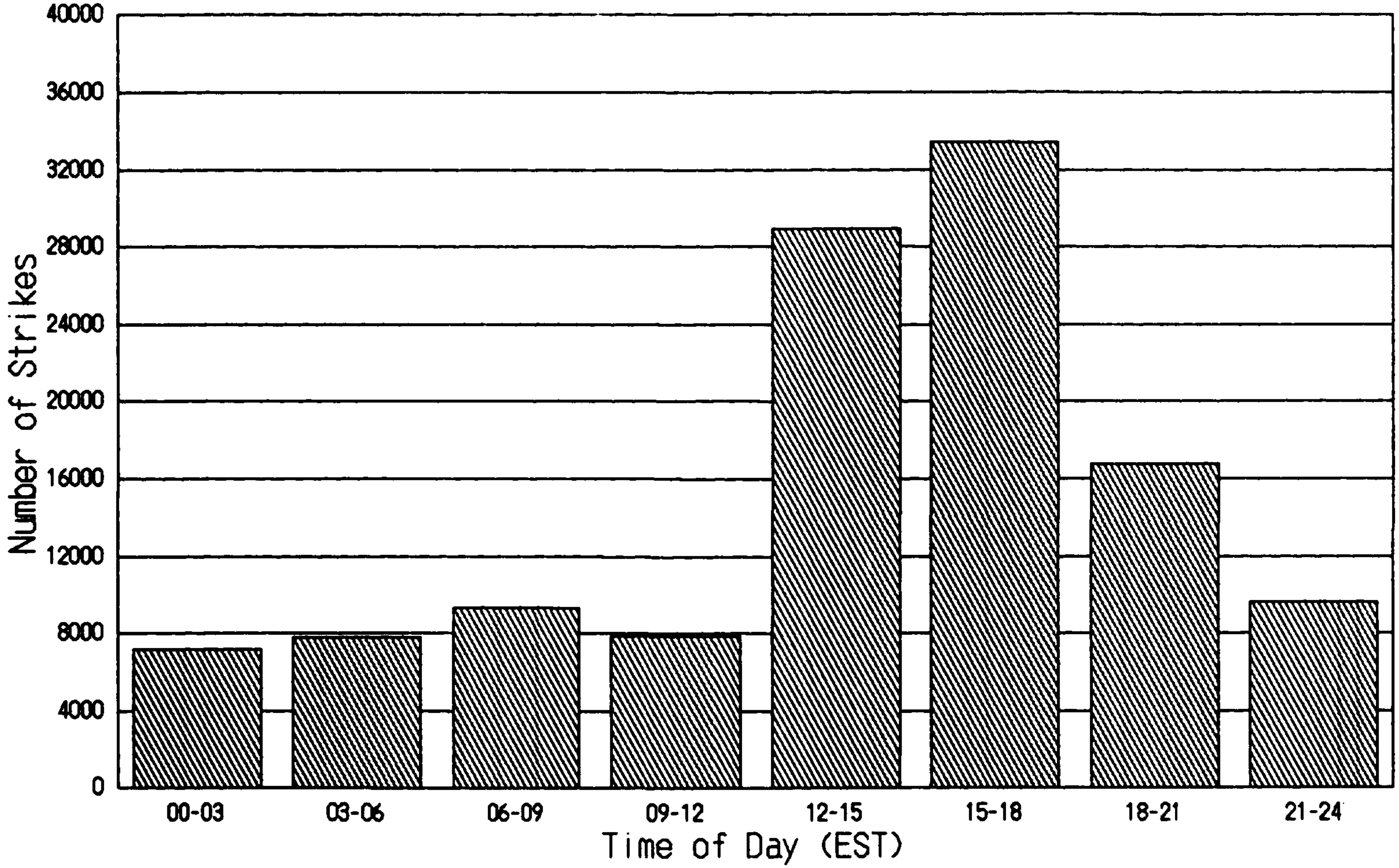

Fig 10. Lightning Strikes Detected by LLP Within 100 KM of Complex 40 During Each 3-Hour Period of the Day (Data Recorded During 1983 and 1984)

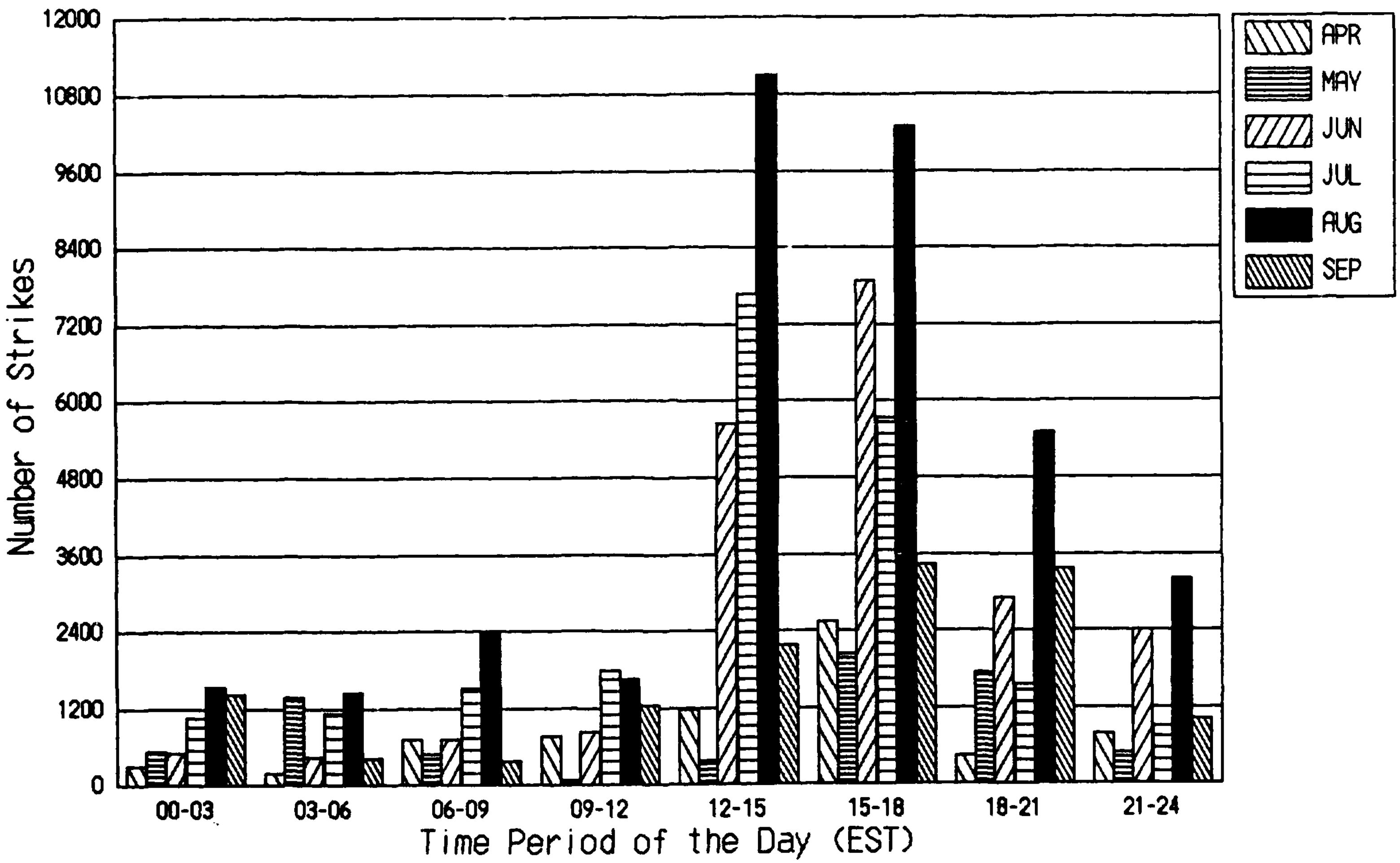

Fig 11. Lightning Strikes Detected by LLP During Each 3-Hour Period (By Month) Within 100 KM of Complex 40
(Data Recorded from Apr-Sep in 1983 and 1984)

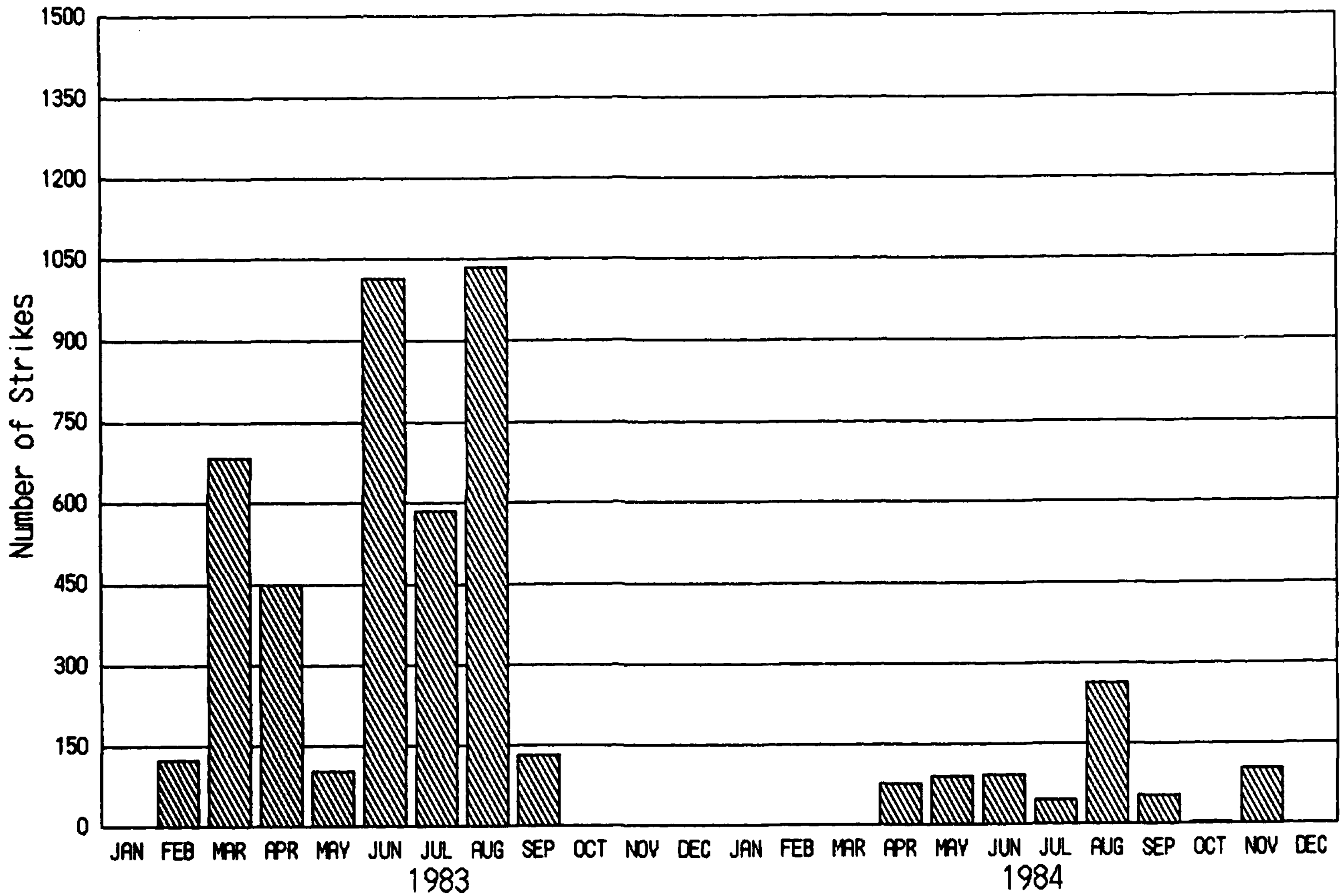

Fig 12. Lightning Strikes Detected by LLP During Each Month
Within 20 KM of Complex 40

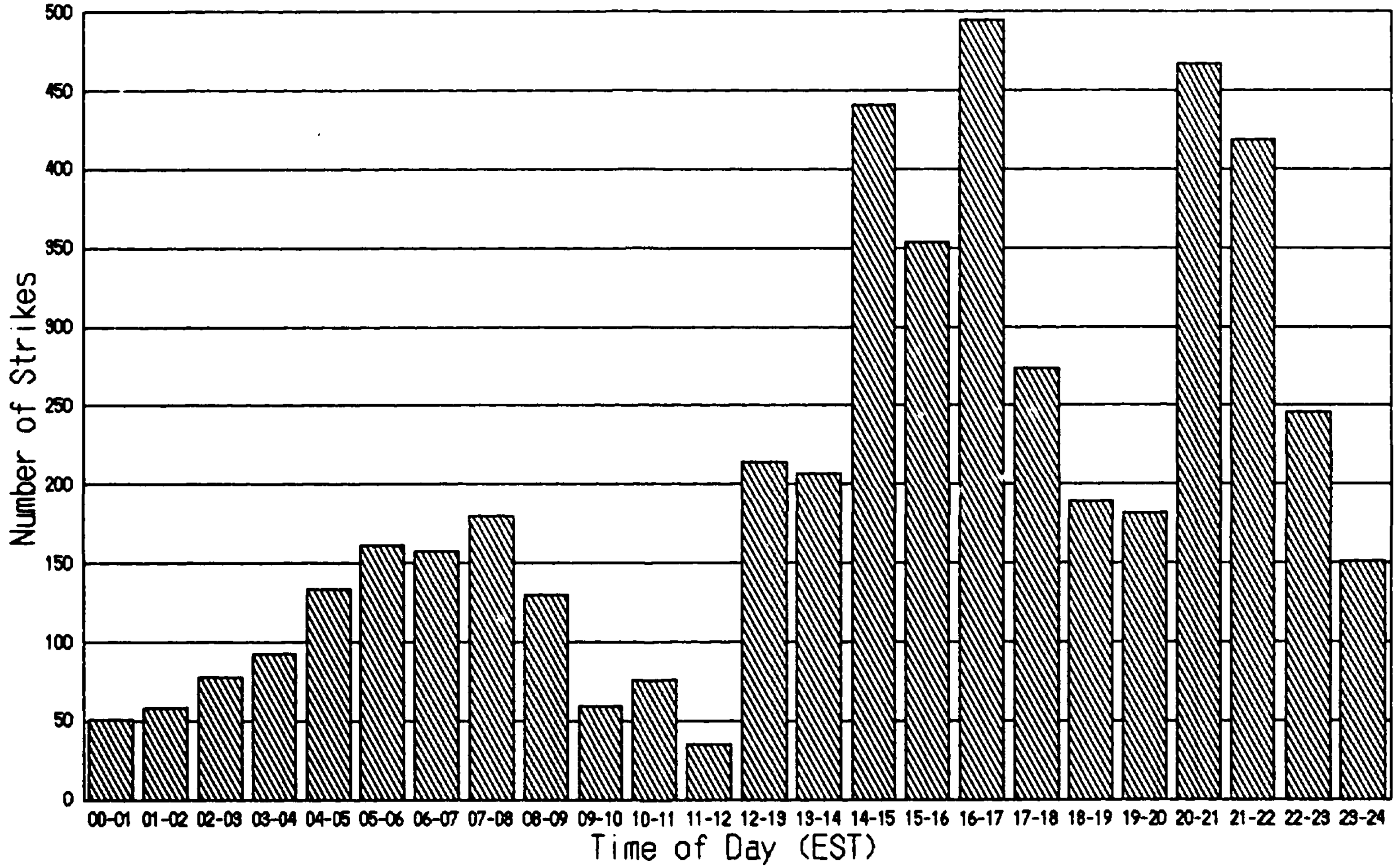

Fig 13. Lightning Strikes Detected by LLP Within 20 KM of Complex 40 During Each Hour of the Day.
(Data Recorded in 1983 and 1984)

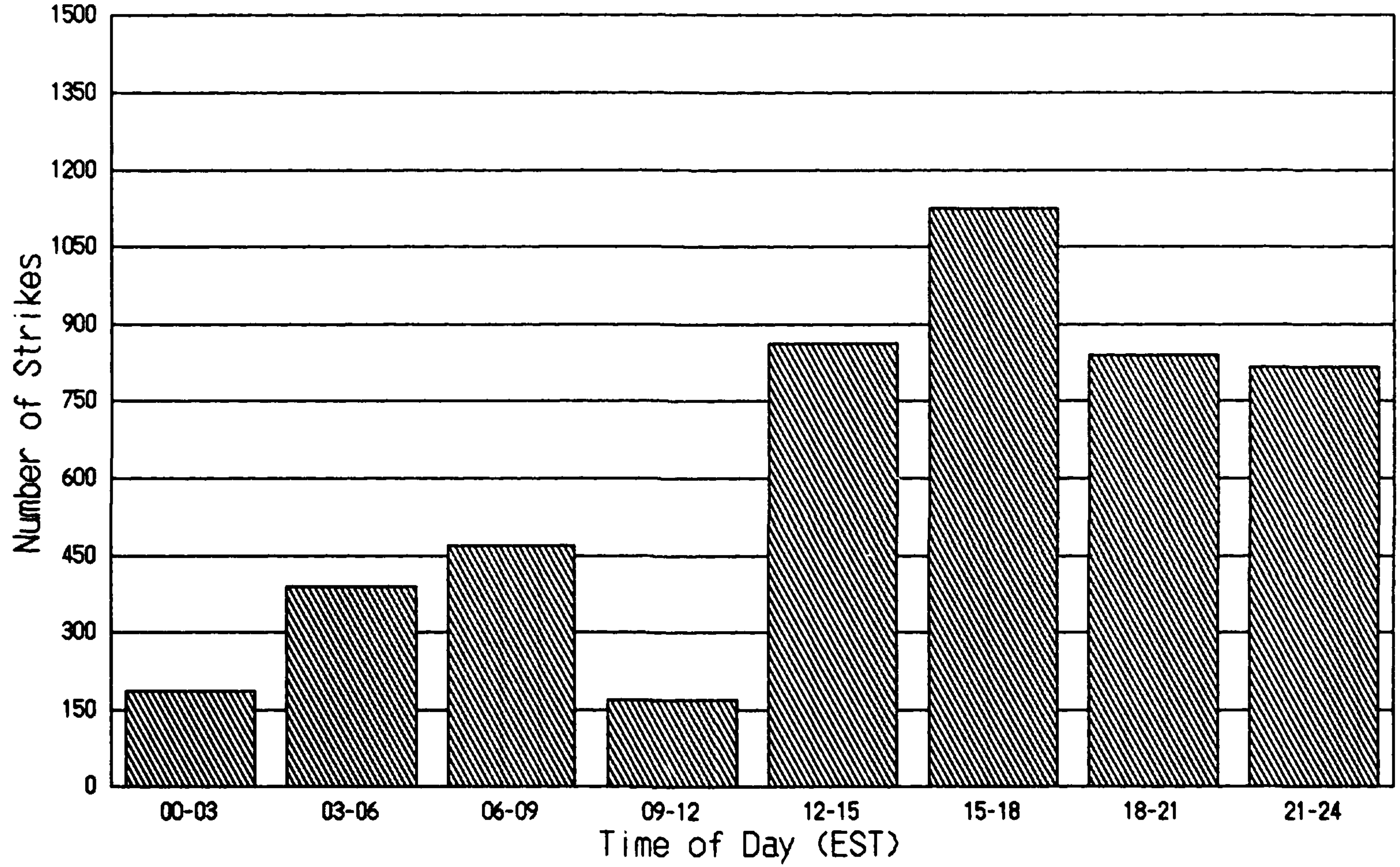

Fig 14. Lightning Strikes Detected by LLP Within 20 KM of Complex 40 During Each 3-Hour Period of the Day (Data Recorded in 1983 and 1984)

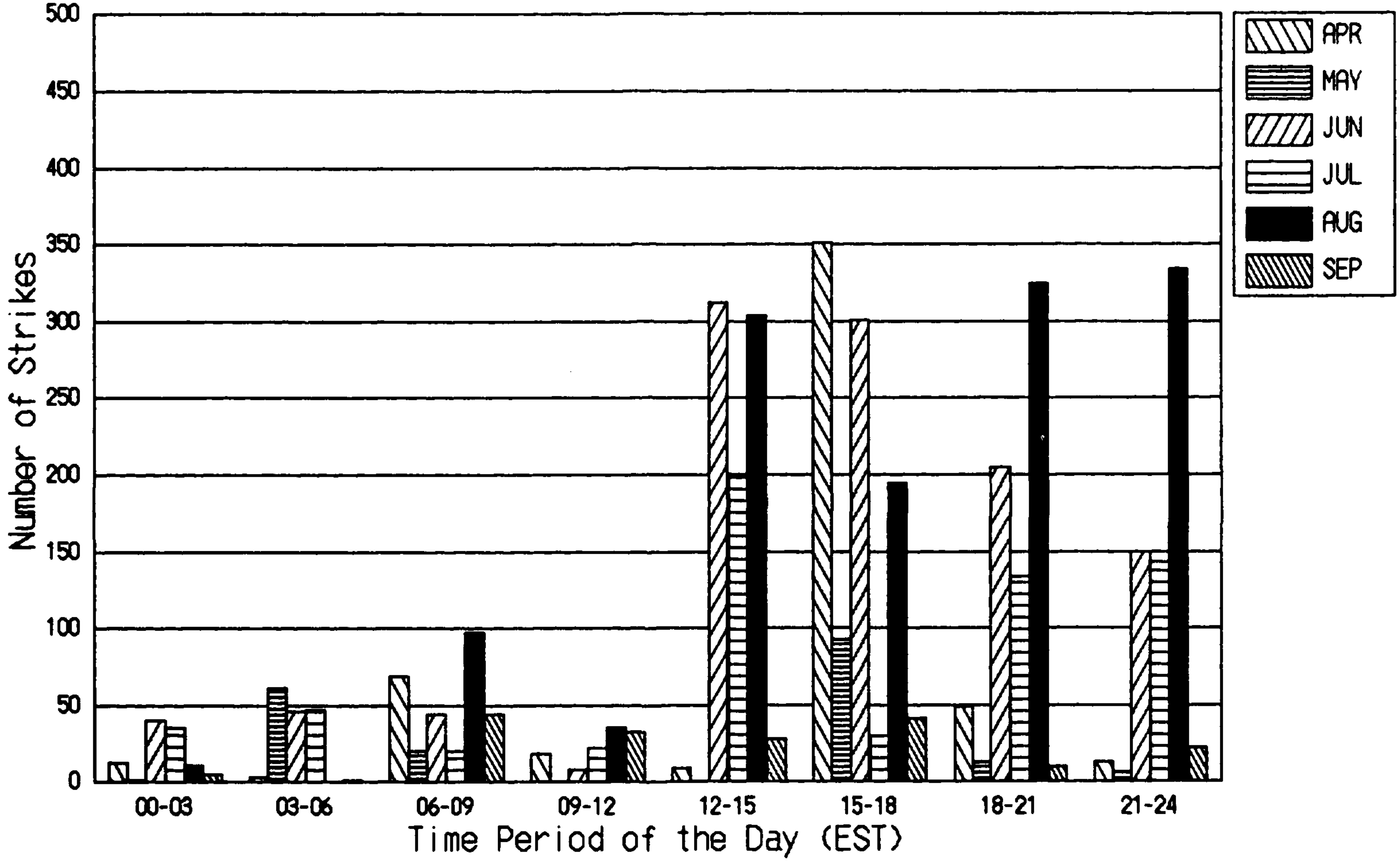

Fig 15. Lightning Strikes Detected by LLP During Each 3-Hour Period (By Month) Within 20 KM of Complex 40
(Data Recorded from Apr-Sep in 1983 and 1984)

Since much of this analysis and the analysis in the next chapter used 3-hour groups, Figures 10 and 14 show the 3-hour group diurnal variation of lightning. They do not have the same resolution as the 1-hour group charts, but show the same trends.

Figure 11 takes the data used in Figure 10 and breaks it down by month. Again, since there are only two years of data, any conclusions on annual fluctuations must be drawn with caution. This set of data shows August to have the most lightning during 7 of the 8 time groups. It also suggests that late in the summer, i.e., September, a greater percentage of the lightning comes later in the day. Actual lightning counts in July and August start to fall off around 3:00 p.m., but activity in September did not decrease until after 9:00 p.m.

Finally, Figures 12 through 15 are the same as Figures 8 to 11, but only represent lightning within 20 kilometers (10.8 nautical miles) of Complex 40. This is the approximate range that the first constraint prescribes. These four charts show some of the real limitations of using only two years of data to analyze the lightning launch constraints. Figure 12 shows that, relative to 1983, 1984 had minimal activity in the Cape area. There were less than 1000 flashes recorded within 20 kilometers during the whole year. Figure 13 shows a sunrise (5:00 a.m. to 8:00 a.m.) peak which is "caused by the land breeze dying out and moving back on shore" (41), as well as mid-afternoon and mid-evening peaks. The data are spread so thin in Figure 15 that I did not try to draw any conclusions here. The chart is presented simply to show what was recorded for those two years.

Analysis of the LLP Data

The LLP data are analyzed to find possible answers to two questions. 1) Are there discernable spatial distributions of lightning on the Cape that can be used in the model to be developed in Chapter 4? 2) What would the launch availability have been in 1983/1984 given the current constraint concerning lightning within 10 nautical miles and 30 minutes, and what would happen if the constraint were changed?

Spatial Distribution. If a spatial distribution can be found, it must be discernable on a scale small enough to distinguish micro-climatological effects, e.g., land/water interfaces, convergence zones, sea breeze fronts, etc. If the analysis leads to a distribution that conflicts with the experience of meteorologists who have worked in the area, or with area climatology, one would suspect that the data are not representative of long-term conditions at the Cape, and would need to be very cautious in using such a distribution, since there may not be enough data from those two years to show real trends. Single, very large storm systems could skew the data to make it unrepresentative of the true distribution.

The spatial pattern is a rather complicated distribution to determine. Factors that interplay include the numerous land/water interfaces, converging/diverging land/sea breezes, changing water temperatures with the changing of the year, and the variability of lightning activity based on low-level winds. "Hot spots" or "quiet areas" are functions of all these variables, and there may not be enough data to resolve the details of the distribution.

I chose a relatively small area around CCAFS/KSC to analyze because I anticipated that this region would have the greatest variability in the smallest area since this area has many land/water interfaces, and converging/diverging land/sea breezes. The area of interest extends from 28.3 to 28.9 degrees north and from 80.5 to 80.9 degrees west. This corresponds to the area shown in Figure 6 and is approximately 36 X 21 nautical miles, or 756 square nautical miles. I divided that region divided into 600 small "squares"--each 0.02 degrees on a side.

Using a FORTRAN program to sort the LLP data set, I determined the number of cloud-to-ground lightning strikes that occurred within each 0.02 degree square of the region. An example of the densities is shown as a grid in Figure 16 along with contours of the values in Figure 17. The full set of contours is located in Chapter 5. Figures 16 and 17 represent all flashes within the region over the two year period. The contours in Chapter 5 are broken into 3- and 12-hour time groups. The most striking feature in Figures 16 and 17 is the area where there are as many as 380 flashes in a 1.26 square nautical mile area. Adjacent and to the south of the highest flash density is a flash density of only 17. The area with the high flash density is about 2-3 miles west of the shuttle landing facility (SLF) over the Indian River and near a relatively large section of Merritt Island, and extends to the west into Titusville. (As a rough scale of distance, the shuttle landing facility is about 3 miles long). The area to the south with the small density is over a large section of the Indian River.

Air Force meteorologists who provide weather support for CCAFS/KSC are aware of what appear to be "hot spots" for lightning activity. Based on his experience in the area, Capt Tom Strange (the KSC staff meteorologist assigned to Detachment 11, Second Weather Squadron) and

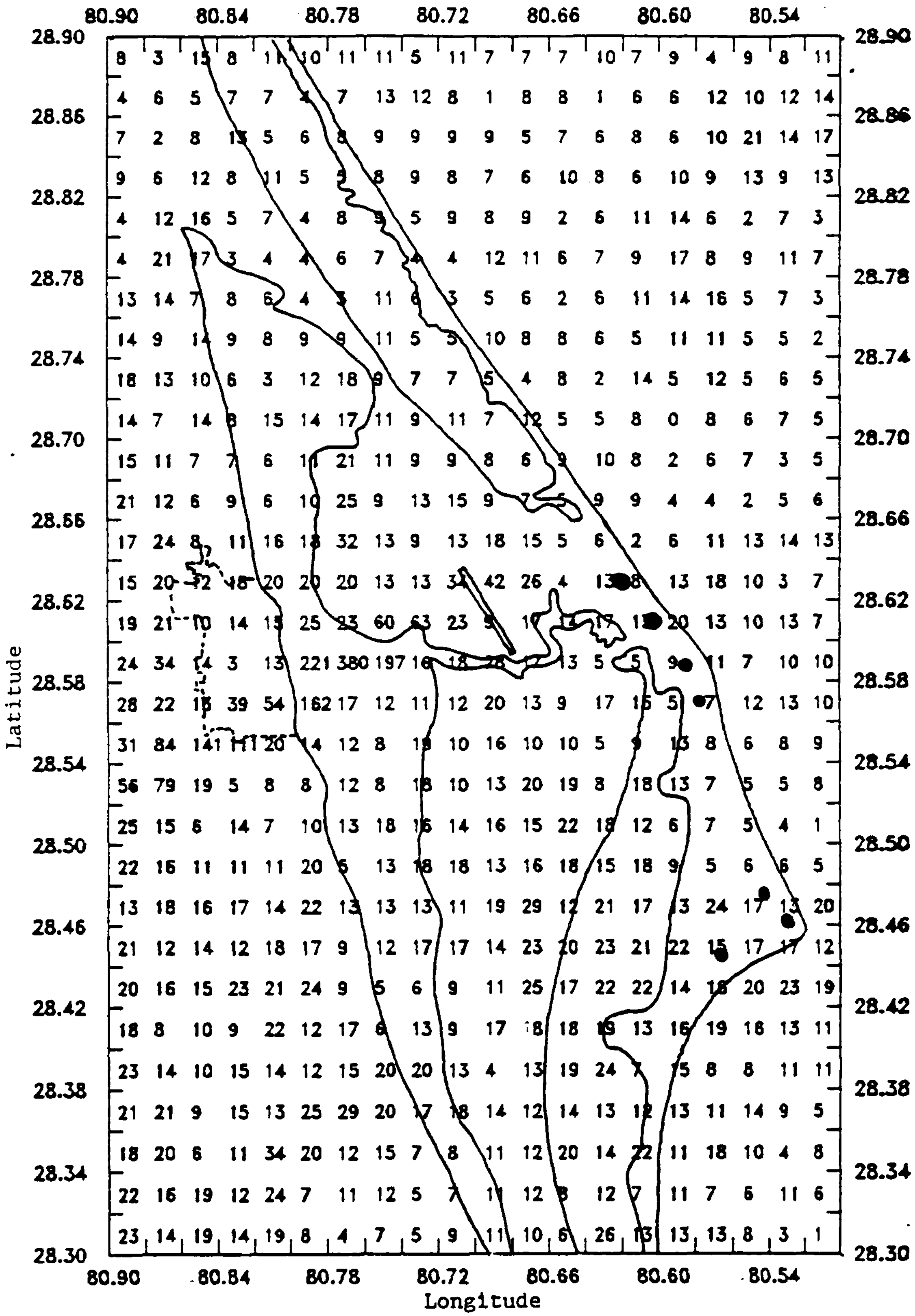

Fig 16. Number of Cloud-To-Ground Lightning Strikes Detected by LLP on the Cape During 1983 and 1984 (0000 to 2400 EST)

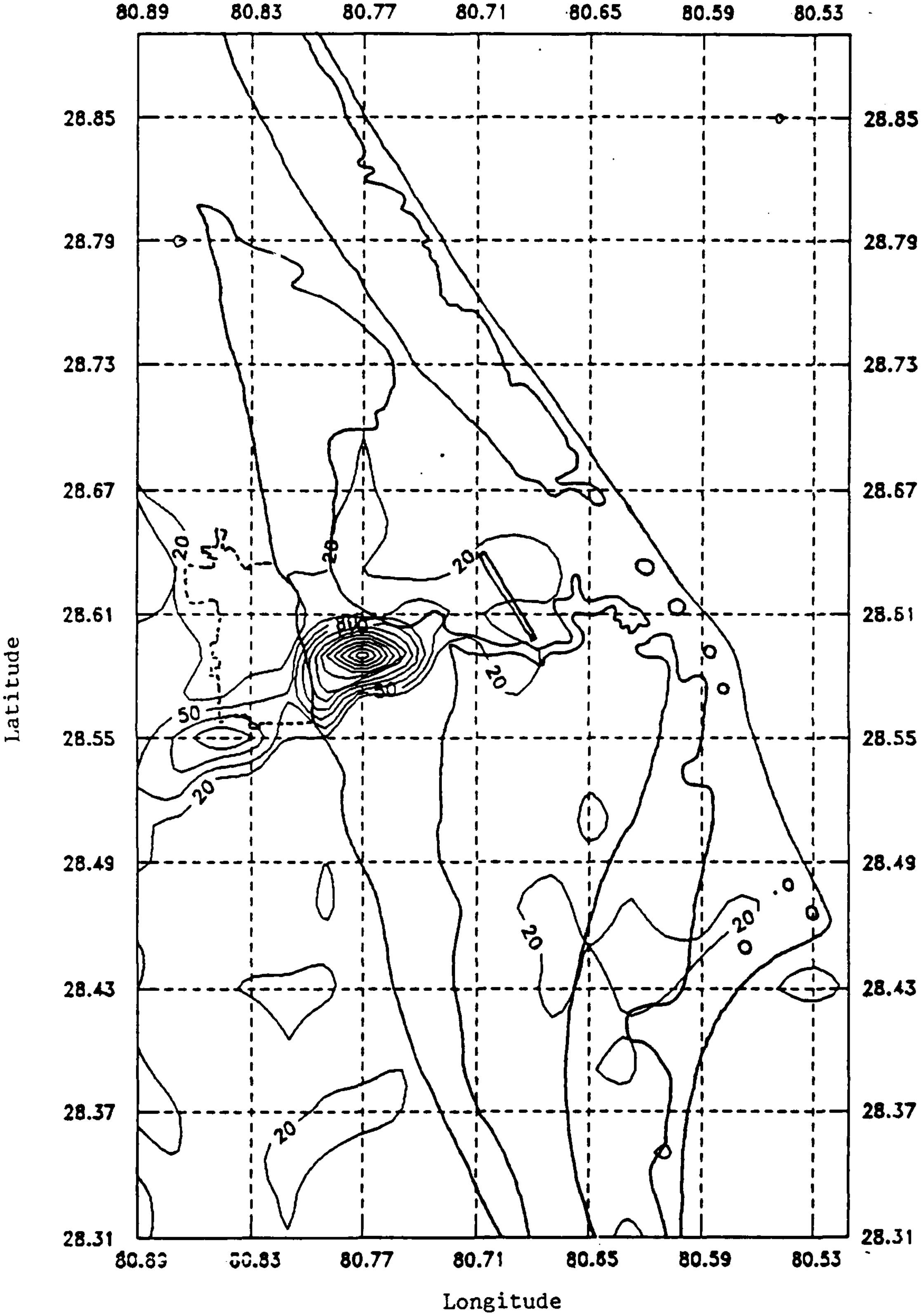

Fig 17. Contours of Cloud-To-Ground Lightning Density on the Cape During 1983 and 1984 (0000 to 2400 EST)

John Weems (civilian forecaster with Detachment 11 at the Cape Canaveral Forecast Facility), surmised there would be a high flash density near the north end of Merritt Island (41; 44).

Launch Availability. The purpose of this part of the thesis is to show the impact of cloud-to-ground lightning on launch availability. Only LLP data are used here. Based on the distributions found in the previous section, I anticipated the launch availability would vary, depending on the year and a given site's location. Indeed, the differences were greater than an order of magnitude in many cases.

To do this analysis, I selected 9 sites on and around the Cape. Seven of the sites were launch pads/complexes. I also used the Port Area (an area on the southeast side of the Cape), and Patrick Air Force Base (about 20 miles south of the Cape). I chose the launch sites since they are the locations where lightning within 10 nautical miles really has significance. The other two areas were used to further show how launch availability is a function of location. Normally, one would not expect major disparities over distances of 5 to 20 miles. However, due to the unique shape of the Cape and its surroundings, marked differences occur over short distances.

The sites I chose and their coordinates are listed in Table 3. All of those sites are identified on the map of the Cape in Chapter 2, Figure 6. Patrick AFB is slightly south of the mapped area.

As an indicator of launch availability, I actually found the lost launch availability, i.e., amount of time when launching would not have been permitted. I wrote a FORTRAN program that read the LLP data file and determined whether or not a given lightning flash was within a specified range of the site. If so, I recorded the amount of downtime

Table 3. Various Sites on the Cape and Their Coordinates

Site #	Identity	Latitude	Longitude
1	PAD 39B	28.626879	80.621082
2	PAD 39A	28.607993	80.604349
3	COMPLEX 41	28.583176	80.583105
4	COMPLEX 40	28.561706	80.577425
5	COMPLEX 36	28.468081	80.541118
6	COMPLEX 46	28.458205	80.528637
7	COMPLEX 17	28.445503	80.565883
8	PORT AREA	28.413333	80.610000
9	PATRICK AFB	28.255341	80.607528

(lost time) the flash would cause. (Note, that if a flash had occurred within range one minute earlier, the next flash would cause only one more minute of additional downtime). The outputs of the program are the minutes of downtime in a given month, and the average percentage of downtime per month.

To see the effect of changing the constraint, I found the downtime for 10 different delay times (6, 12, ... 60 minutes), and 10 different standoff distances (2.5, 5.0, ... 25.0 nautical miles). I calculated the downtime for all possible combinations of delay, standoff distance, site, month and year. Tables 4 & 5 are examples of the results of this investigation. In this example, the only delay (DEL) is 30 minutes. The standoff distances (DIST) are 10 and 20 nautical miles. All summer months (M) and both years (YY) are listed. A further discussion is in Chapter 5.

From Table 5, an example of operational interest can be investigated: "What if the delay were left at 30 minutes but the standoff distance were changed from 10 to 20 nautical miles?" Looking just at July (month 7) as an example, the downtime for Complex 36 (site 5) would have increased by 5 times (from 1.34 percent to 6.71 percent)

Table 4. Minutes of Lost Launch Availability for Nine Sites Around the Cape

DEL	DIST	M	YY	SITES 1	2	3	4	5	6	7	8	9
30.0	10.0	4	83	1070	1318	1391	1540	1214	1238	1168	912	480
30.0	10.0	4	84	218	230	226	226	208	208	208	180	84
30.0	10.0	5	83	212	219	222	224	319	323	315	304	171
30.0	10.0	5	84	338	372	379	379	478	541	460	454	329
30.0	10.0	6	83	1680	1902	2252	2222	2353	2316	2276	2141	1659
30.0	10.0	6	84	108	118	116	116	110	105	110	110	61
30.0	10.0	7	83	3073	2855	2019	1638	472	436	523	518	557
30.0	10.0	7	84	231	348	431	439	724	719	744	636	485
30.0	10.0	8	83	2015	1941	1680	1646	754	704	768	841	606
30.0	10.0	8	84	407	450	517	529	575	606	547	681	701
30.0	10.0	9	83	1169	934	621	533	252	242	256	256	225
30.0	10.0	9	84	525	501	545	541	667	700	642	666	350
30.0	20.0	4	83	2119	2146	2210	2233	2300	2300	2268	2209	1429
30.0	20.0	4	84	330	330	337	367	367	367	366	356	356
30.0	20.0	5	83	360	374	376	376	376	357	376	376	332
30.0	20.0	5	84	1215	1236	1222	1178	1146	1127	1153	1182	1092
30.0	20.0	6	83	3707	3770	3787	3802	3931	3934	4041	4190	3962
30.0	20.0	6	84	245	245	213	213	183	182	243	312	350
30.0	20.0	7	83	4329	4319	4083	3963	4095	4038	4122	4305	1893
30.0	20.0	7	84	2034	2064	1820	1931	1894	1986	2026	2284	1965
30.0	20.0	8	83	3458	3428	3033	2905	2870	2862	3092	3479	2237
30.0	20.0	8	84	1768	1771	1668	1696	2129	2125	2137	2307	2055
30.0	20.0	9	83	2017	2008	2027	2009	2000	1989	1967	2003	695
30.0	20.0	9	84	2170	2109	1908	1757	1535	1524	1509	1519	1208

Table 5. Percent of Lost Launch Availability for Nine Sites Around the Cape

DEL	DIST	M	SITES 1	2	3	4	5	6	7	8	9
30.0	10.0	4	1.52	1.83	1.91	2.09	1.68	1.71	1.63	1.29	0.67
30.0	10.0	5	0.62	0.66	0.67	0.68	0.89	0.97	0.87	0.85	0.56
30.0	10.0	6	2.11	2.39	2.80	2.76	2.91	2.86	2.82	2.66	2.03
30.0	10.0	7	3.70	3.59	2.74	2.33	1.34	1.29	1.42	1.29	1.17
30.0	10.0	8	2.71	2.68	2.46	2.44	1.49	1.47	1.47	1.70	1.46
30.0	10.0	9	2.00	1.70	1.38	1.27	1.09	1.11	1.06	1.09	0.68
30.0	20.0	4	2.89	2.93	3.01	3.07	3.15	3.15	3.11	3.03	2.11
30.0	20.0	5	1.76	1.80	1.79	1.74	1.70	1.66	1.71	1.75	1.59
30.0	20.0	6	4.67	4.75	4.73	4.75	4.86	4.87	5.06	5.32	5.10
30.0	20.0	7	7.13	7.15	6.61	6.60	6.71	6.75	6.89	7.38	4.32
30.0	20.0	8	5.85	5.82	5.27	5.15	5.60	5.59	5.86	6.48	4.81
30.0	20.0	9	4.95	4.87	4.65	4.45	4.18	4.15	4.11	4.16	2.25

if the standoff distance were changed from 10 to 20 nautical miles. For 1983 alone, Table 4 shows the increase in downtime would have been 8.68 times (from 472 minutes to 4095 minutes). The change factors for downtime for all nine sites are shown in Table 6.

Table 6. Increase in Downtime (Multiplicative Factor) for Various Sites if Range is Changed from 10 to 20 Nautical Miles

Site	Overall Change Factor	Change Factor for 1983	Change Factor for 1984
1	1.93	1.41	8.81
2	1.99	1.51	5.93
3	2.41	2.02	4.22
4	2.84	2.42	4.40
5	5.01	8.68	2.62
6	5.22	9.26	2.76
7	4.85	7.88	2.72
8	5.71	8.31	3.59
9	3.70	3.40	4.05

I also looked at the percentage of downtime on a diurnal basis. Due to the limited amount of data, I only used July and August. Figure 18 shows the percentages of downtime for July from 15-18 EST for various standoff distances and delay times. For this portion of the analysis, only downtimes for Complex 40 were found. The downtimes for all of the 3-hour groups in July are in discussed in Chapter 5.

Standoff Distance (NM)	6	12	18	24	30	36	42	48	54	60
25.0	4.4	6.8	8.7	10.5	12.1	13.4	15.0	16.2	17.8	19.5
22.5	3.0	4.8	6.4	8.0	9.4	10.7	12.1	13.2	14.8	16.1
20.0	2.2	3.6	4.7	5.9	6.9	7.8	8.8	9.5	10.4	11.8
17.5	1.8	3.1	4.2	5.3	6.3	7.1	7.9	8.6	9.4	10.2
15.0	1.7	2.9	3.9	4.9	5.8	6.5	7.3	7.9	8.6	9.3
12.5	1.5	2.4	3.1	3.9	4.5	4.9	5.4	6.0	6.5	6.9
10.0	0.4	0.8	1.2	1.6	1.9	2.3	2.7	3.1	3.4	3.7
7.5	0.2	0.4	0.6	0.9	1.1	1.3	1.5	1.7	1.9	2.2
5.0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0
2.5	0.1	0.1	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0

Delay Time (Minutes)

Fig 18. Percentage of Lost Launch Availability at Complex 40 from 1500 to 1800 Eastern Standard Time in July Due to Cloud-To-Ground Lightning During 1983 and 1984

IV. Analysis of Simulated Lightning Data

The Need for a Simulation Model

Chapter 3 showed some of the information that can be derived from real data. Perhaps the best analyses of the impact of lightning on launch availability could be done using actual lightning data. However, two years of data are not sufficient to make conclusions. There is too much variability from year to year and, perhaps, neither 1983 nor 1984 was really representative of a normal year. More data is being collected and processed for 1985 through 1988, but that data will not be available in time to analyze for this thesis. Therefore, a simulation of lightning events was used. Having developed a model, any amount of data can be simulated for an analysis--though the limitations of the model must be recognized and considered.

Purpose of the Model

This model is not intended to predict lightning activity or precise numbers for launch availability. It is intended to indicate some possible trends or patterns and to develop a method that can be used when more data is available. This model simulates thunderstorms around CCAFS/KSC and lightning events within those storms. The outputs of the model are the times and locations of lightning events. Model data are then analyzed to show the sensitivity of launch availability to standoff distance and delay time.

The data in chapter 3 is taken from the LLP network. However, that LLP data only represents about 80% of the negative cloud-to-ground lightning. Positive strokes and any strokes that do not strike the ground are not included in the data set. However, the first lightning launch constraint restricts launching when any type of lightning is detected within 10 nautical miles within 30 minutes of launch time. Therefore, a model that accounts for cloud-to-cloud, in-cloud, and cloud-to-air strikes as well as cloud-to-ground strikes is needed. This model includes all types of lightning.

Valid Time Period of the Model

This is a summertime (April-September) lightning model for the CCAFS/KSC area. There are three reasons for choosing these months:

1. Most Florida lightning occurs during the summer. Therefore, lightning will have its greatest impact on launch availability during the summer.

2. More data exist for summer months. This allows better approximations for the distributions of lightning activity. Air mass (summer) thunderstorm statistics should not be applied to frontal (winter) storm activity.

3. Although, on average, there is one more thunderstorm day in October than in April, April is modeled because the only months for which data are available for both 1983 and 1984 are April through September. The results for April are included, since April is the start of the air mass thunderstorm season at the Cape; however, April has no significant impact on the results for the other months since there is no correlation between months. The one exception to this lack of correlation is when a storm is scheduled to begin late on the last day of April, it may last into May. Since there are, on average, only

3 thunderstorm days per year in April, and most of the storms in April occur during the day, this would be a low probability event, and the sampling size would be too small to bias the model results.

Distributions and Parameters Used in this Model

Several sources were used to define the parameters of the model. All of the sources have limitations in their applicability to this problem, and none of the data were originally collected as input to this model. However, by considering a variety of sources and using some meteorological experience, reasonable values can be deduced. The distributions used and assumptions made in developing this model are meant to approximate the real world.

Characteristics of thunderstorms and storm systems that determine the lightning activity can be analyzed on at least three scales. The microphysics of the cloud, (e.g., freezing and thawing of ice crystals), and the internal characteristics of the cloud, (e.g., vertical motions), are actually more likely to predict lightning activity, but these processes are not well understood by the scientific community (11). Therefore, I used a meteorological scale--parameters that can be observed from outside the cloud and modelled from climatology and experience. The following parameters define thunderstorms on this scale and are considered in the model:

1. Frequency of thunderstorms (diurnal and annual distributions). More frequent storms cause greater loss of launch availability and impact pad preparations.

2. Time duration of air mass thunderstorms. A long storm may

cause a launch to be cancelled on a given day, but a short storm may only cause launching to occur later in the launch window.

3. Flash rate within the storm. In practice, the flash rate can give indications of the storm's life and whether it is getting stronger or dissipating. Only average flash rate is modelled.

4. Total number of strikes within the storm. This is simply a function of the duration and average flash rate. It can be used as an indication of the intensity of the storm.

5. Size of the storm. Storms centered outside the standoff area may extend into the standoff area if they are large enough.

6. Geographical location of a given thunderstorm. When modelled with the motion of a storm, this parameter can determine whether a storm system is moving into or out of the launch area.

7. Time of the first flash of lightning. The first flash, if it is within the standoff range (i.e. 10 nautical miles), defines the beginning of lost launch availability.

8. Spatial distribution of lightning within the storm. Although most flashes within a storm occur near a central point, single, destructive flashes can occur several miles from the storm center.

9. Motion of the storm. As mentioned above, the motion of a storm can be monitored for its approach into, departure from, or development in the standoff area.

Table 1 indicates that there is an average of 76 thunderstorm days per year in the KSC area. For each mont' from April to September, there is an average of 3, 8, 13, 16, 14, and 10 thunderstorm days per month, respectively. This yields an average of 64 thunderstorm days per summer. Though useful, this information is not sufficient to analyze the impact of lightning due to diurnal variations in lightning activity. As shown by Table 7, the probability of a storm at a given time during the day for a given month varies considerably. For example, in July, there is a 1.3% chance of a storm being in progress between 0600 and 0900. By the afternoon, however, the probability increases to 20.2%. These values are derived from hourly surface observations at KSC from 1969-1970 and 1973-1980. (The location from which these values were collected changed in March 1978 (44). The site was moved from a point near the coast to its present location near the shuttle landing facility. The change in location would have an impact on these numbers by moving the observation station closer to the Indian River hot spot mentioned in Chapter 3). Although for that period of record, no storms had been reported between 0300 and 0600 in May, for the purposes of this simulation, a small probability was included (.01%). There is no meteorological reason why storms cannot occur during those hours--they just never did during that period of record. Hence, a zero probability would be unrealistic.

Table 7. Percent Frequency of Thunderstorms at Cape Canaveral

	00-03	03-06	06-09	09-12	12-15	15-18	18-21	21-24
JAN	0.1	0.0	0.1	0.0	0.2	0.2	0.6	0.2
FEB	0.0	0.0	0.0	0.2	0.5	0.4	0.2	0.4
MAR	0.6	0.8	0.4	0.3	0.4	0.3	1.2	1.4
APR	0.6	0.1	0.2	0.7	1.9	1.0	0.8	0.4
MAY	0.8	0.0	0.5	1.7	6.1	7.6	6.9	2.8
JUN	0.8	0.4	0.9	1.9	7.0	14.3	11.3	2.6
JUL	0.8	0.1	1.3	2.6	12.0	20.2	12.7	4.3
AUG	1.3	1.3	0.8	2.8	8.4	14.9	8.7	2.6
SEP	3.7	2.4	1.8	1.7	6.6	8.3	6.8	4.1
OCT	0.8	0.2	0.5	0.2	1.0	1.4	1.6	0.9
NOV	0.0	0.3	0.1	0.0	0.2	0.8	0.8	0.7
DEC	0.0	0.1	0.0	0.2	0.4	0.6	0.1	0.0

(Adapted from 40:3.17)

The following steps were used to develop a probability distribution for thunderstorms during the summer:

1. Normalize the percent frequency data for each month. This gives the percentage of times a storm will fall within a given time period if it occurs during a given month. These values are found by dividing the percent frequency of each 3-hour group for a given month by the sum of all the percent frequencies for that month. For example, if a storm occurs in April, the probability that it occurs between 0000 and 0300 is 0.6/(.6 + .1 + .2 + .7 + 1.9 + 1.0 + .8 + .4) = .1052632. The normalized values for April are:

Time of Day	Probability
00-03	0.1052632
03-06	0.0175439
06-09	0.0350877
09-12	0.1228070
12-15	0.3333333
15-18	0.1754386
18-21	0.1403509
21-24	0.0701754

Note that all times are local standard time (Eastern Standard Time).

2. Since during each month a different number of storms occur, on average, the normalized probabilities are weighted according to the average frequency of storm days per month. For example, since there is an average of 3 storm days in April and 16 storm days in July, the normalized values for April and July are multiplied by 3 and 16, respectively. The weighted probabilities for April are then:

Time of Day	Weighted Probability
00-03	0.3157895
03-06	0.0526316
06-09	0.1052632
09-12	0.3684211
12-15	1.0000000
15-18	0.5263158
18-21	0.4210526
21-24	0.2105263

3. After all the weighted probabilities are calculated, the whole set is normalized again to find the probability that, given a thunderstorm, it will occur at any given time period during any given month. Table 8 shows the final probability distribution.

Table 8.. Probabilities of a Storm Occurring at a Given Time of Day During a Given Month at Cape Canaveral

Time	Apr	May	Jun	Jul	Aug	Sep
00-03	.0049342	.0037864	.0041454	.0037037	.0069700	.0163312
03-06	.0008224	.0000473	.0020727	.0004630	.0069700	.0105932
06-09	.0016447	.0023665	.0046636	.0060185	.0042892	.0079449
09-12	.0057566	.0080462	.0098453	.0120370	.0150123	.0075035
12-15	.0156250	.0288716	.0362723	.0555556	.0450368	.0291314
15-18	.0082237	.0359712	.0740992	.0935185	.0798866	.0366349
18-21	.0065790	.0326581	.0585539	.0587963	.0466452	.0300141
21-24	.0032895	.0132526	.0134726	.0199074	.0139399	.0180968

One may think that it would be easier to just normalize the summer months' values in Table 7 to attain the values in Table 8. However, if that is done, the probabilities would not be adjusted for the fact that each month has a climatological value for the number of storms. For example if the summer months of Table 7 were simply normalized, and 64 storms were distributed according to that scheme, April would get, on average, only 1.8 storms instead of 3, and July would get over 17 instead of 16. There is not enough precision in the numbers in Table 7 to rely on a simple normalization.

The duration of a thunderstorm (defined as the time interval between the first and last lightning flash) can vary over at least an order of magnitude. A storm may last for less than 30 minutes or more than 5 hours. To find a distribution for thunderstorm duration, 79 duration data points collected by Piepgrass and Krider were used (36:11196-11197). These durations were collected via the electric field mill network at KSC/CCAFS. Note that durations of storms that are determined using all lightning flashes may be longer than for the ones using only cloud-to-ground flashes. Nicholson, et al (34:4), cite an example where cloud-to-ground flashes in a small thunderstorm were detected for 26 minutes while a 40-minute duration was observed for all lightning.

An hypothesized lognormal distribution with a mean of 112.8 and a standard deviation of 90.46 fits the data collected by Piepgrass and Krider and passes a chi squared goodness-of-fit test at alpha = .20. This test indicates there is no reason to conclude the data are poorly fitted by the lognormal (112.8, 90.46) distribution.

The average flash rate in Florida thunderstorms was also derived from the data collected by Piepgrass and Krider (36:11196, 11197). Although the values presented by Piepgrass and Krider for duration and flash rate are from the same storms, it was found that the correlation between duration and flash rate was only .13--very little correlation. Therefore, based on the results of this study, the distribution for the flash rate was considered independent of the duration of the storm. The distribution used for the flash rate was lognormal with a mean of

2.543 and a standard deviation of 3.122. This distribution passes a chi squared goodness-of-fit test at alpha = .075. While this is not as good as the test for the duration distribution, this is still good evidence that the distribution is adequate. Figures 19a and 19b show the relative probabilities of selecting a given duration and given average flash rate.

There were some restrictions placed on the allowed values of the duration and flash rate. A duration in excess of 350 minutes was not allowed, and a flash rate of greater than 18 flashes per minute was thrown out. In addition, if the duration was over 250 minutes and the average flash rate was over 12 flashes per minute, a new flash rate was determined. These restrictions were made because lognormal distributions can range from zero to infinity (in theory). Such extremes can skew the data severely, and do not occur in Florida air mass thunderstorms. Some storms in other parts of the country do have much longer durations. For example, a mesoscale convective complex (MCC) is a large storm, perhaps the size of Oklahoma and Kansas, and may have a duration on the order of 18 to 24 hours. Some systems that almost look like an MCC come through Central Florida, but they are usually just systems of many individual thunderstorms (44). Air mass thunderstorms that I am modelling depend on thermal convection to sustain themselves. The diurnal changes in temperature and low-level winds (sea breeze) prevent these types of storms from enduring as an MCC would.

The number of strokes in a storm is modelled as the duration of the storm times the average flash rate. Flashes are assumed to occur with a simple exponential distribution of time between flashes. The

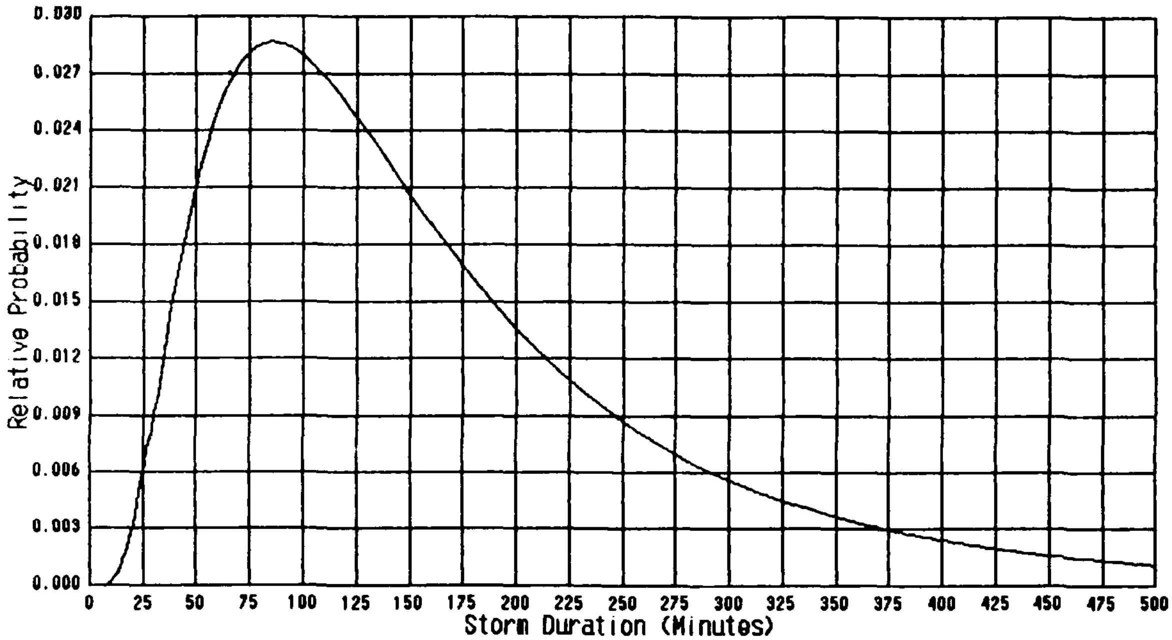

Fig 19a. Relative Probability of Storm Duration (From Lognormal Distribution with Mean=112.8, Sdev=90.4)
(Durations >350 Minutes are not Used by Model)

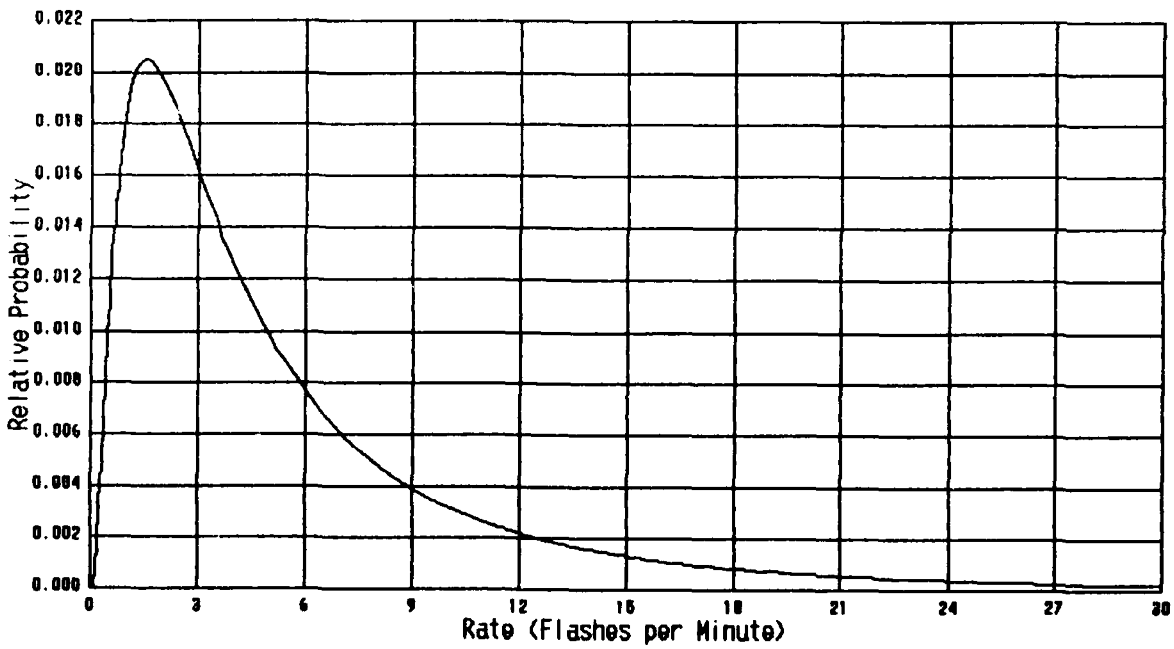

Fig 19b. Relative Probability of Lightning Flash Rates (From Lognormal Distribution with Mean=2.5, Sdev=3.1)
(Flash Rates > 18/Min are not Used in Model)

reciprocal of the average flash rate described above was used as the mean of that distribution. It could not be determined with sufficient degree of certainty from the cloud-to-ground data available that the flash rate changes with time in a predictable manner. When the relationship between flash rate and time is determined, it can be incorporated into the model.

To get reasonable values for the size of a Florida summer thunderstorm, two sources and personal experience were used. Data collected by Maier and Krider from 268 storms in 1978 reveal the mean and maximum areas defined by cloud-to-ground lightning strikes to be 450 and 1550 square kilometers, respectively (27:336). Nicholson, _et al_, describe a "small thunderstorm" from September, 1986, that had a diameter of 7 kilometers (34:1). Assuming circular storms, for simplicity, these numbers suggest minimum, mean, and maximum radii of approximately 2, 7, and 12 nautical miles. Using these values, the radius was chosen from a triangular distribution with a minimum of 2, and a maximum of 12 nautical miles. The mode of the distribution, however, was a variable based on the duration of the storm. Generally, small storms will not last as long as large storms. I derived the following empirical relation between the duration and the mode of the radius:

$$\text{mode} = \text{duration}^{(1/2.4)} \qquad (1)$$

This relationship makes longer storms have a higher probability of being larger and shorter storms will tend to be smaller. For example, when the duration is 350 minutes, the mode of the size is 11.48 nautical miles, and when the duration is only 20 minutes, the radius distribution has a mode of 3.48 nautical miles. The triangular distribution prevents storms from being too small or too large. Note, it is assumed the area defined by cloud-to-ground lightning (based on the data collected my Maier and Krider (27:336)) is representative of the area that would be defined by all types of lightning within a storm.

The modeling of the geographic position of the storm is not based on a collected data set. When more data are available to justify it, a more complex model may consider such factors as the fact that more lightning occurs west of the shuttle landing facility. See the discussion in Chapter 5 about this "hot spot." Similarly, more storms will occur west of the Cape during the day, but night time thunderstorms are often observed off shore. Radar data can be used to find locations of storms, but that data is very hard to work with and was not available for this project.

Thunderstorms are recorded by surface observers when the observer can hear thunder. Typically, thunder can be heard from about 10 nautical miles away. Assuming that to be true, the storm center on any of those 64 thunderstorm days could be as far away as 10 nautical miles plus the radius of the storm itself. Therefore, the 64 thunderstorm days that occur on average each year, probably define a circular area about 17 nautical miles in radius (adding the 10 nautical miles from which thunder can be heard and the average size of Florida thunderstorms as discussed above).

The analysis portion of this thesis considers standoff distances as great as 30 nautical miles. Therefore, the maximum range at which a thunderstorm could conceivably affect a launch is 30 nautical miles plus the radius of the storm. Once the size of the storm has been determined, the range is selected by taking the square root of a number selected from a set of numbers uniformly distributed from zero to the square of the maximum range. A simple uniform distribution from zero to the maximum range will tend to lump storms at the center of the circular area--the number of storms must increase as the square of the distance from the center to assure a uniform distribution within the area.

For this model, the only effect of the bearing to the storm on the results is that it will affect the range of lightning strikes within the storm. A lightning strike on the south side of a storm to the south may not affect launch activity, but if the storm had been to the north, it may have had an impact. The bearing was considered to be uniformly distributed from 0 to 360 degrees (0 to 2 pi radians).

In a one-year period, the number of storms that occur within an influential range is related to the number of storms that occur within hearing range of the weather observers--about 17 miles. If the radius is increased from 17 miles to 37 miles, the area covered increases by a factor of 4.7 times. If the 64 thunderstorm days that occur on average each summer at CCAFS/KSC could be interpreted as 64 individual storms, the expected number of storms within 37 nautical miles would be about 300. As pointed out in chapter 2, Piepgrass and Krider recorded 79 storms on 62 days which indicates that more than one storm can occur on each of the 64 thunderstorm days recorded by weather observers. However, the ratio of 79/62 would be too high of a factor to apply to the expected number of storms that will occur within a 37 mile radius. As the circle expands from 17 to 37 nautical miles, the percentage of ocean area increases. Fewer storms occur over the water which is immediately adjacent to the land than occur over the area just west of the cape area. Also, the "hot spot" mentioned above would already be enclosed by a 17 nautical mile radius. This area represents a significant portion of lightning in the area. See Chapter 5. Therefore, a compromise was made on the average number of storms to expect during a given summer. The average used for this simulation was 325 storms per season. Figure 20 shows the spatial distribution of the center points of simulated storms over a one year period.

When the time for a storm to occur is determined, it is based on the distribution in Table 8. If, however, that time is used as the starting point, or the first flash, the lightning distribution will be unrealistically skewed to later parts of the day. To avoid this, the time generated for the storm (storm time) is used as the half-way point through the storm, and the first flash is scheduled to occur at storm time minus one half the duration of the storm. This makes the hourly distributions of the simulated data match the real data (and the real world) better.

More lightning events will occur near the center of the storm than on the outside. Jacobson and Krider (14:116) found that most lightning (nearly 80%) occurs within 5 kilometers of the computed center of a single-charge cloud charge distribution. However, occasional flashes do occur outside the normally recognized boundaries of a storm. To account in general for this variability of flashes over the area of the storm, the range from the center of the storm to the lightning flash was modeled as a triangular distribution with a minimum of 0, a mode of one fourth the radius of the storm, and a maximum of the radius of the storm plus one kilometer. Two factors helped concentrate the lightning

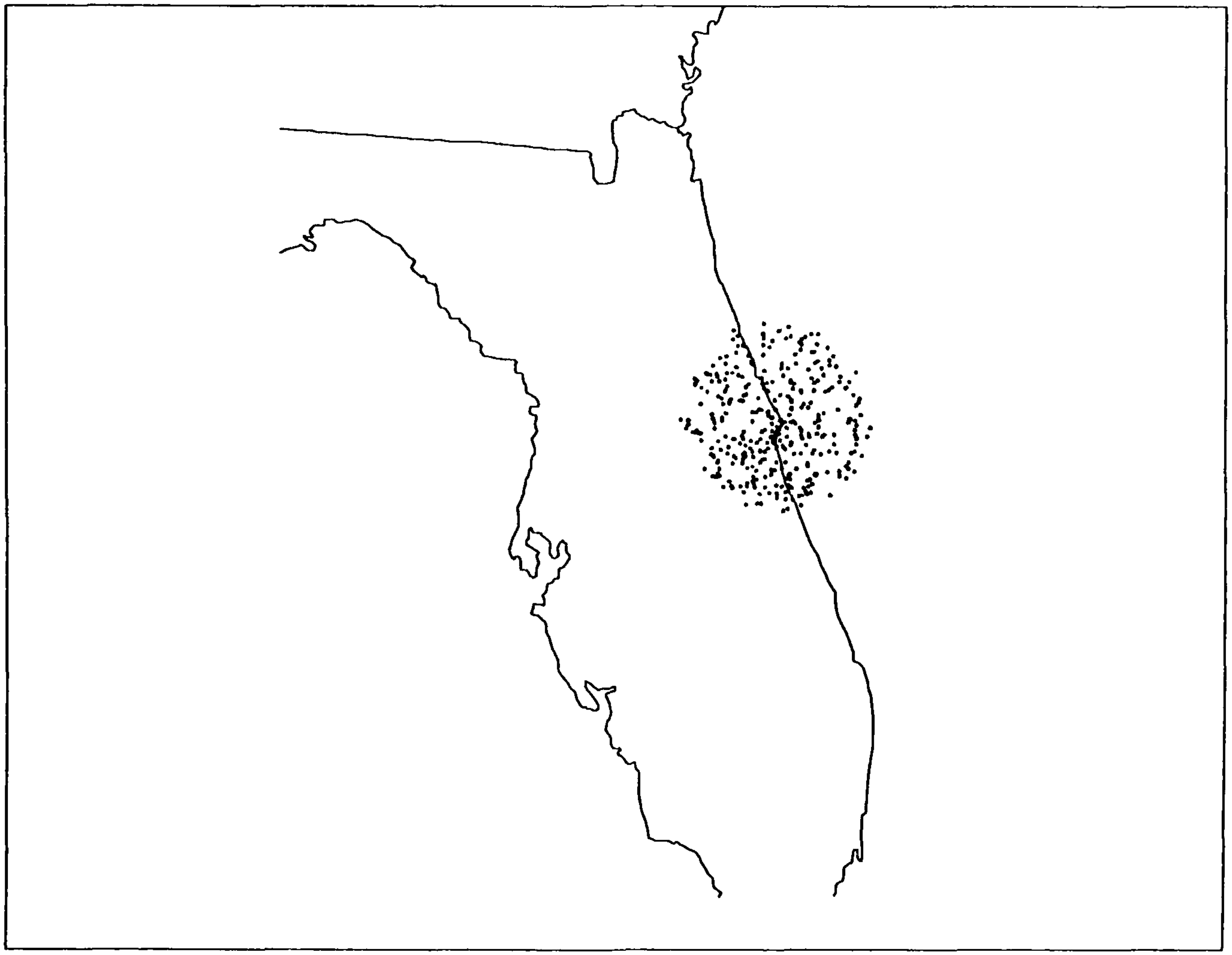

Fig 20. Spatial Distribution of Simulated Thunderstorm Center Points For One Year

at the center of the storm. First, the mode of the distribution is closer to the center than to the edge. Second, the number of flashes was not allowed to increase as the square of the distance from the center of the storm. The bearing from the center of the storm to the lightning flash was modelled as uniformly distributed from 0 and 360 degrees.

In this model, thunderstorms do not move. This is not wholly unrealistic since a significant portion of air mass thunderstorms in the KSC/CCAFS area are products of the sea breeze and may migrate less than 5 miles in their lifetime (34:5). Storms do move, but the effects of some storms moving in and other storms moving away will tend to cancel each other over a period of time. Therefore, stationery storms are used.

Summary of the Distributions Used in the Lightning Model

The following summary of the distributions is a thumbnail sketch of the parameters discussed in the previous section for which a random distribution was used.

PARAMETER	DISTRIBUTION	MIN	MEAN	MODE	SDEV	MAX
Duration (min)	Lognormal		112.8		90.46	
Flash Rate (per min)	Lognormal		2.543		3.122	
Storm Radius (NM)	Triangular	2		*		12
Range to Storm (NM)	Sqrt(Uniform)	0				**
Storm Bearing (Deg)	Uniform	0				360
Range to Flash (NM)	Triangular	0		Radius/4		Radius+1
Flash Bearing (Deg)	Uniform	0				360

* Mode of storm radius is a function of the duration:

$$\text{mode} = \text{duration}^{(1/2.4)} \text{ (NM)} \tag{1}$$

** Maximum value for the uniform distribution is $(30 + \text{radius})^2$ (NM^2)

Running the Model

This model is driven by a SLAM II routine. The steps involved are:

1. Create a storm event.

2. Assign a day and time of day for occurrence.

3. A FORTRAN subroutine is then called that determines the characteristics of the storm, e.g., duration and flash rate.

4. After the characteristics of the storm are determined, the individual lightning strikes within the storm are simulated.

5. When all lightning events have been simulated, control is returned to the SLAM II routine which creates another storm. Steps 2, 3, and 4 are then repeated.

6. After all storms have been simulated for the first year, the whole process is repeated for the next year. When I simulated data for April-September, I used 6 years. When examining the diurnal variations, I simulated July and August for 10 years.

Figure 21 is a flowchart of this model. The code for the model is in Appendix C.

For each distribution in the simulation, I used a different random number stream. That allows for some flexibility in making changes to one distribution without affecting the other distributions. This feature was not used in the thesis, since a major objective was to provide a methodology for analysis. I selected the best distributions I could find and used them. If a sensitivity analysis is done, though, and the parameters of the distributions are changed, the distributions should be independent. (Note that some distributions are inherently dependent on others, e.g., radius is a function of duration).

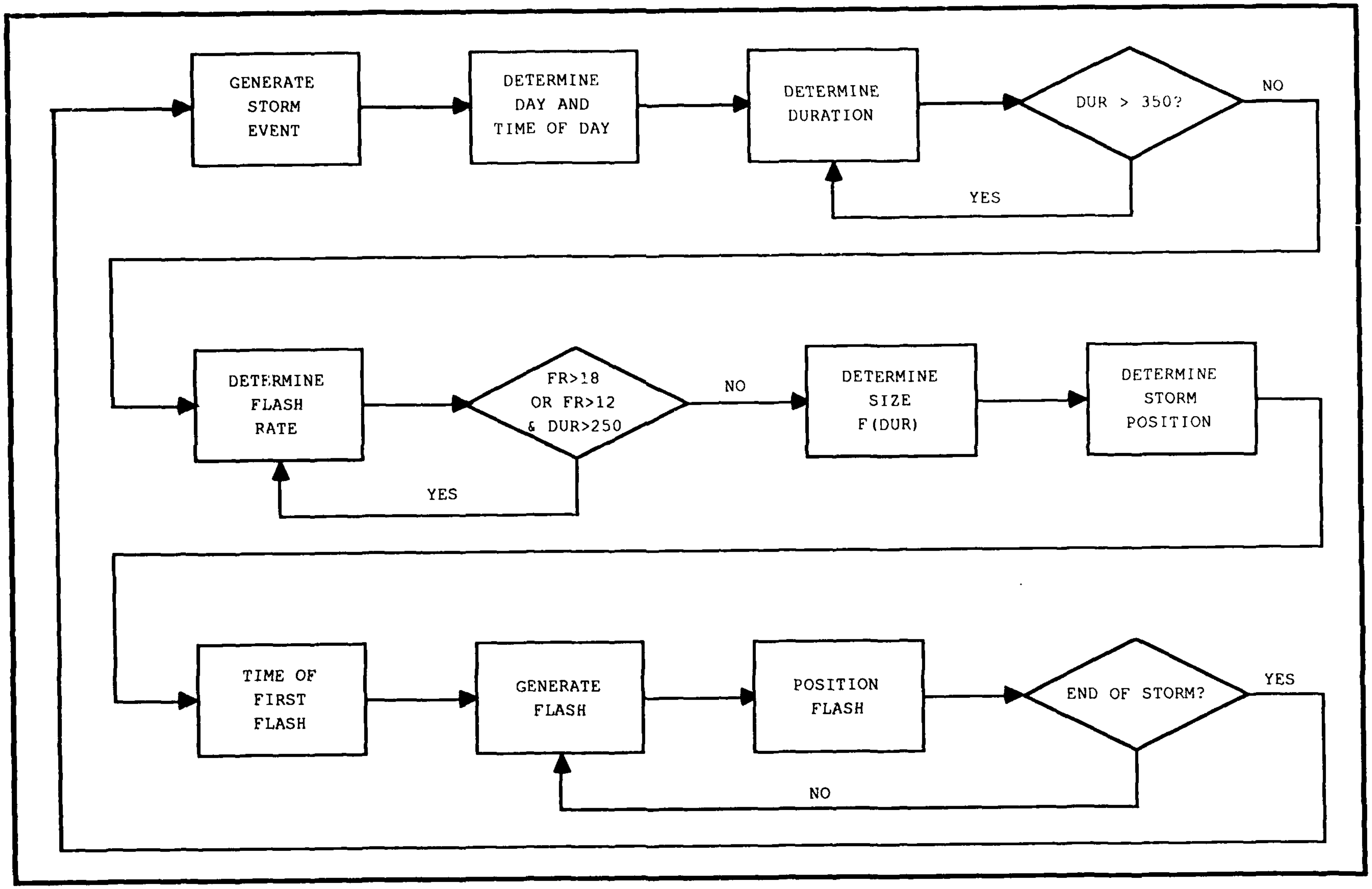

Fig 21. Flowchart of the Lightning Simulation Model

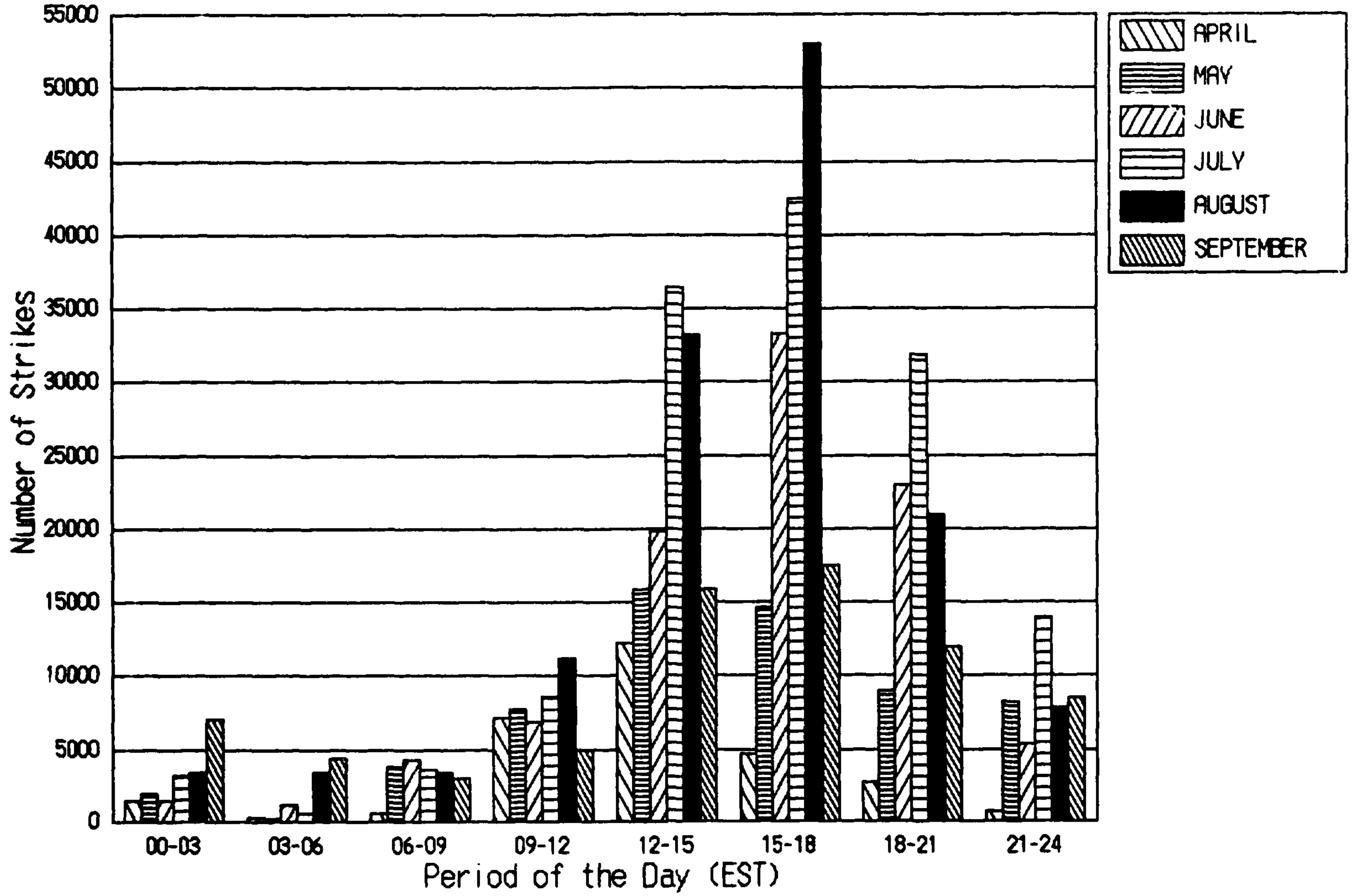

Fig 22a. Diurnal Distribution of Simulated Lightning During Each Month of Six Summers (Apr-Sep) at the Cape

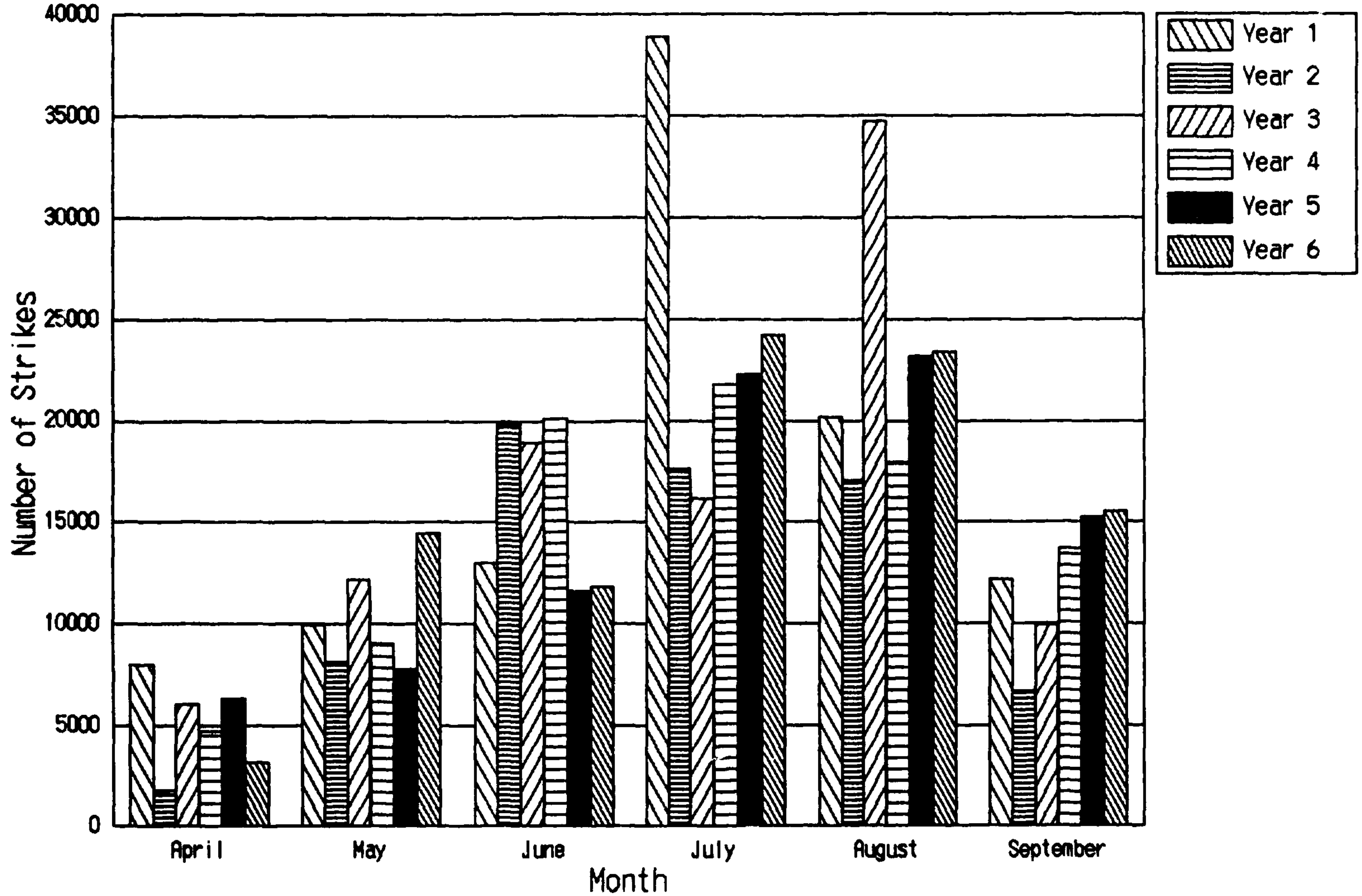

Fig 22b. Monthly Distribution of Simulated Lightning at the Cape During Six Summers (Apr-Sep)

The general characteristics of the simulated data are shown in Figures 22a and 22b. Note that even though all the data were created by the same model, there is variability from year to year. That points out the need to run the model for more than one year of data.

I used this model to generate data that could be used for launch availability. I found launch availabilities for each summer month and for each 3-hour period in July and August. The impact of changing the standoff distance and/or delay time was considered in this analysis.

The goal of this section of the thesis was to develop equations that could be used to estimate what downtime would be associated with a given standoff distance and delay. After determining the downtime for 10 delay times ranging from 6 to 60 minutes, and 10 standoff distances ranging from 3 to 30 nautical miles, I used the 100 data points and a general linear model procedure on SAS to help reduce the data into equations. To account for first and second order effects of changing the range (standoff distance in nautical miles) and/or the delay time (minutes), I postulated a model equation

$$Z = A*R + B*D + C*RR + E*RD + F*DD + G \tag{2}$$

where A, B, C, E, and F are coefficients, G is a constant, R is the range, D is the delay time, RR is the range squared, DD is the delay squared, RD is the range times the delay and Z is the percentage of downtime.

Using SAS I solved for the coefficients and constants for each month and each 3-hour period in July and August. Each equation can be used to generate estimations of downtime for its valid time period. For example, the equation for July downtime is

$$Z = 0.130860*R + .027638*D + .010395*RR + .004269*RD - .000430*DD + .151971 \quad (3)$$

Figure 23 is a plot of the results obtained from that equation. All of the equations and several charts like Figure 23 are in Chapter 5.

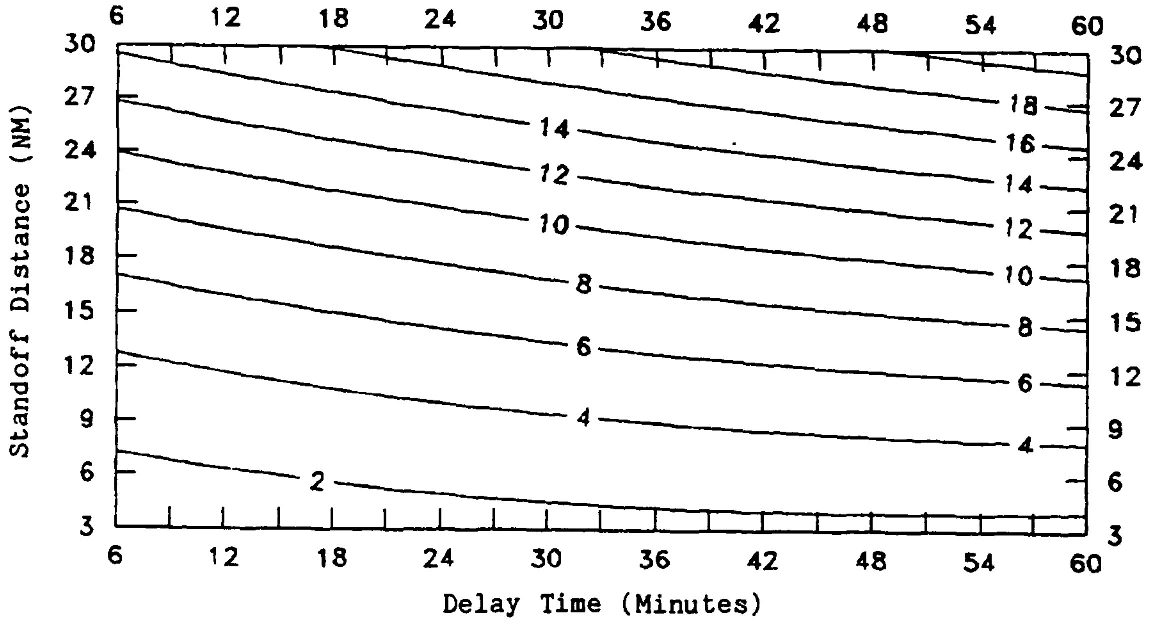

Fig 23. Percentage of Lost Launch Availability in July as a function of Standoff Distance and Delay Time (Based on Simulated Data)

V. Discussion of Results and Conclusions

Introduction

Chapters 3 and 4 described the development of a methodology to analyze the first lightning launch constraint and presented some of the results from a preliminary analysis. The purpose of this chapter is to discuss the results of those chapters and make conclusions where possible. There are three general areas that will be discussed in this chapter: 1) The spatial distribution of cloud-to-ground lightning around the Cape, 2) The launch availability based on the LLP data and 3) The projected launch availability based on the simulated lightning data.

Spatial Distribution of Lightning

Figures 24 to 34 are discussed here. These figures cover the same area of the Cape as Figure 6. The most obvious feature on all these graphics is the high density of lightning on a line from the south side of Titusville, across the Indian River and onto Merritt Island. Concerning that high density area, I noticed several things:

1. The area was distinguishable during every 3-hour period as well as 12- and 24-hour periods. The only period for which it was relatively subdued at all was from 12-15 EST (Figure 28). I suspect that it only seems subdued from 12-15 because at that time of day, thunderstorms are forming all over the area.

2. Generally, there were two lobes to the density distribution. However, from 03-09 (Figures 25 and 26), the western lobe was absent.

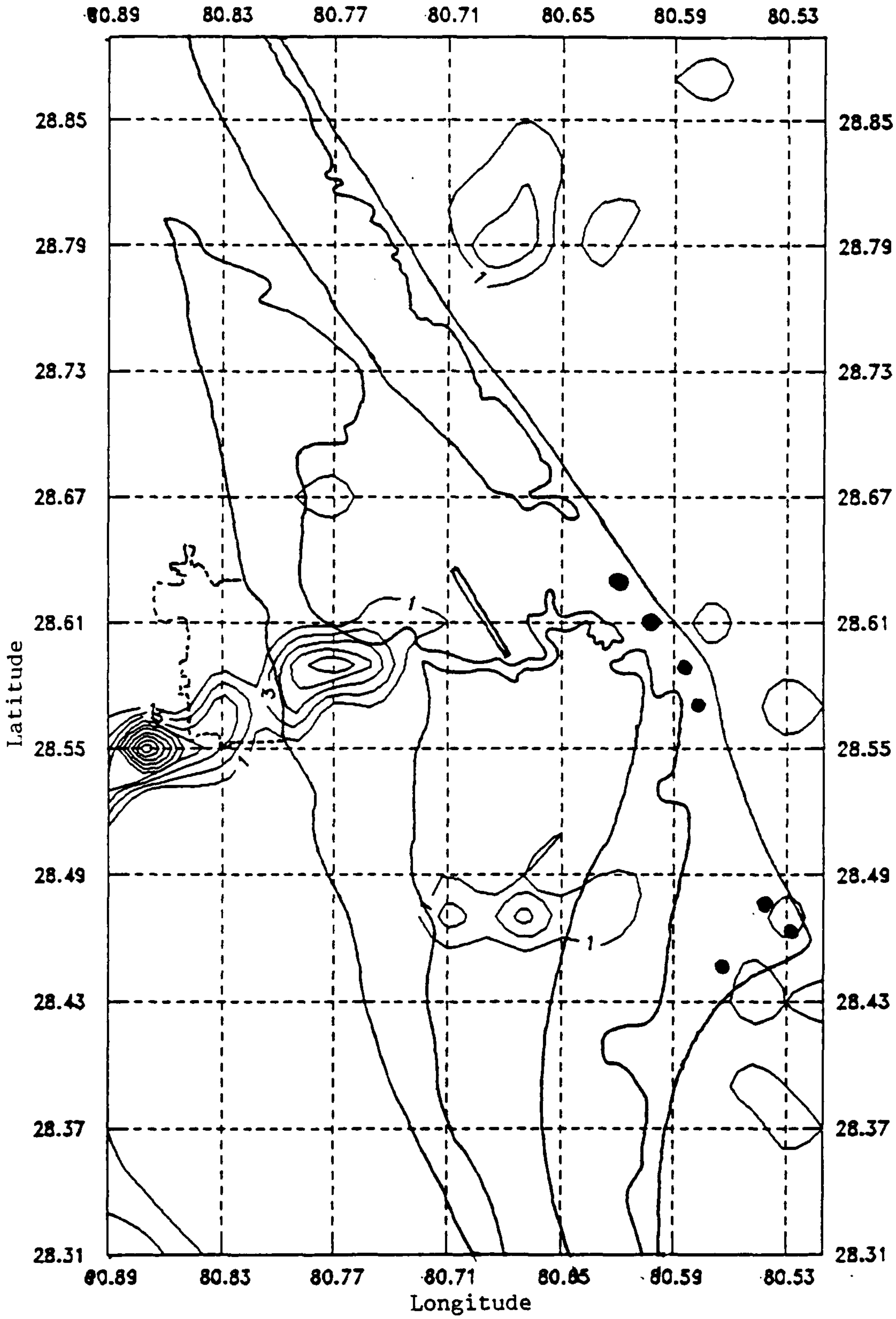

Fig 24. Contours of Cloud-To-Ground Lightning Density on the Cape During 1983 and 1984 (0000 to 0300 EST)

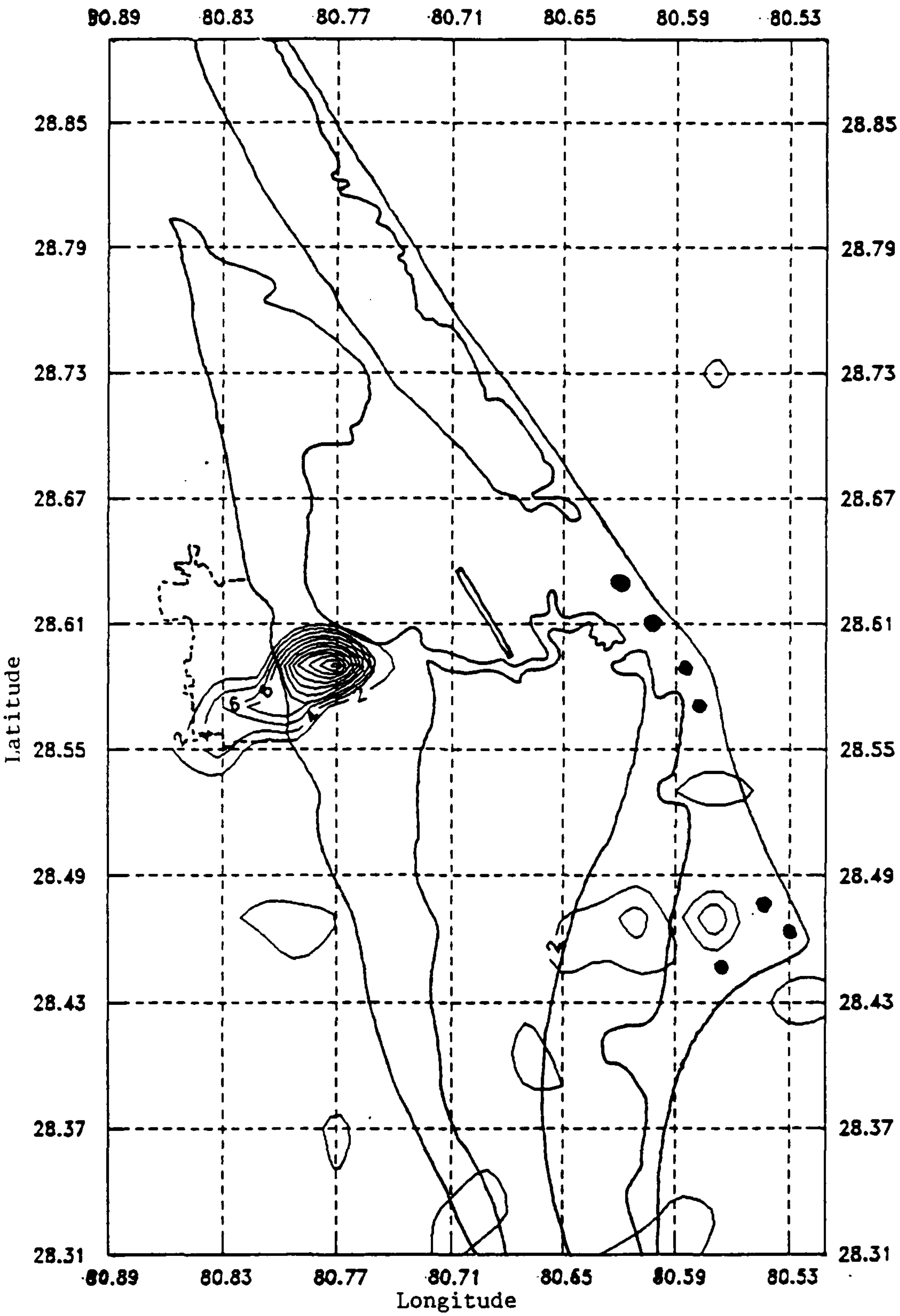

Fig 25. Contours of Cloud-To-Ground Lightning Density on the Cape During 1983 and 1984 (0300 to 0600 EST)

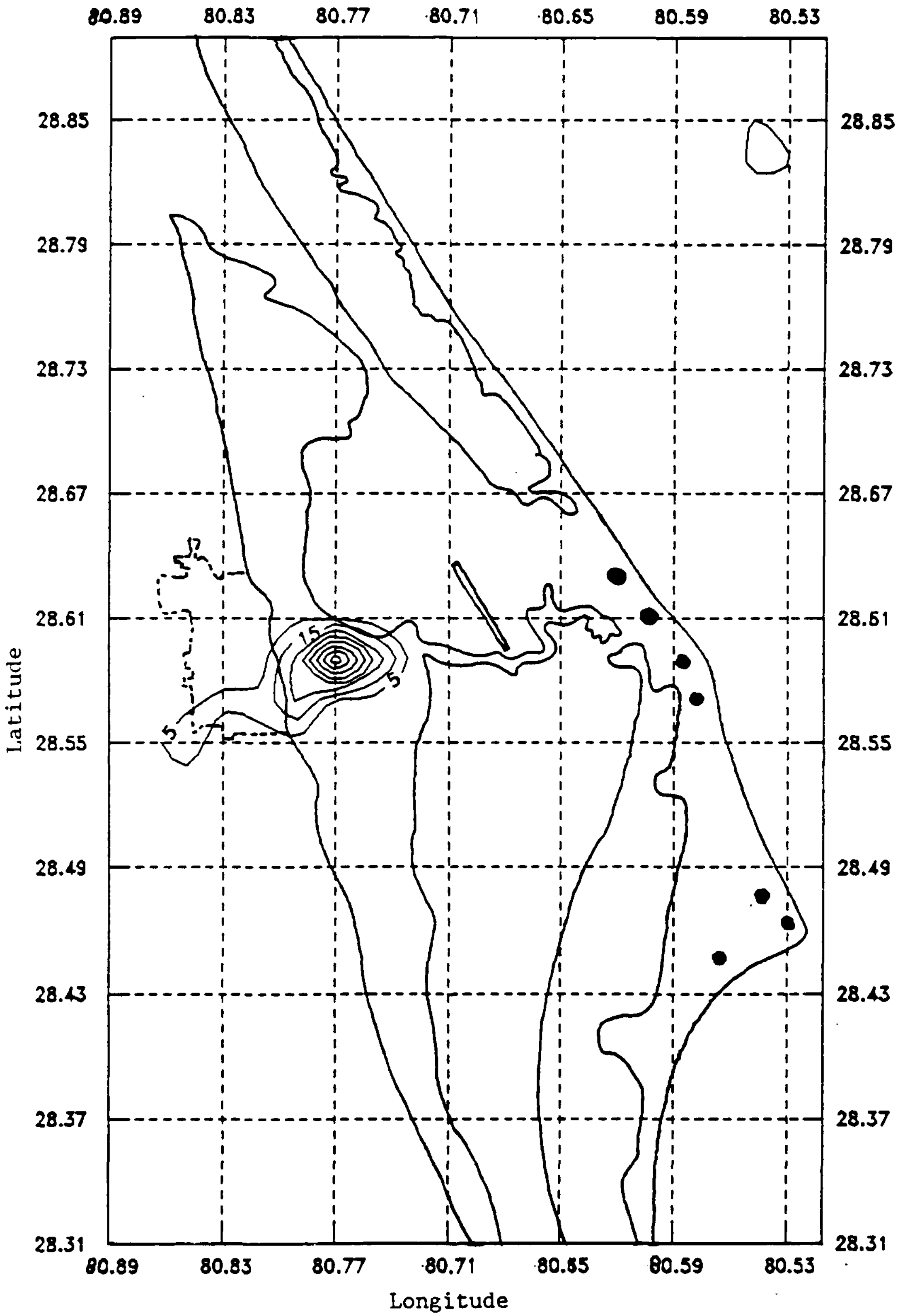

Fig 26. Contours of Cloud-To-Ground Lightning Density on the Cape During 1983 and 1984 (0600 to 0900 EST)

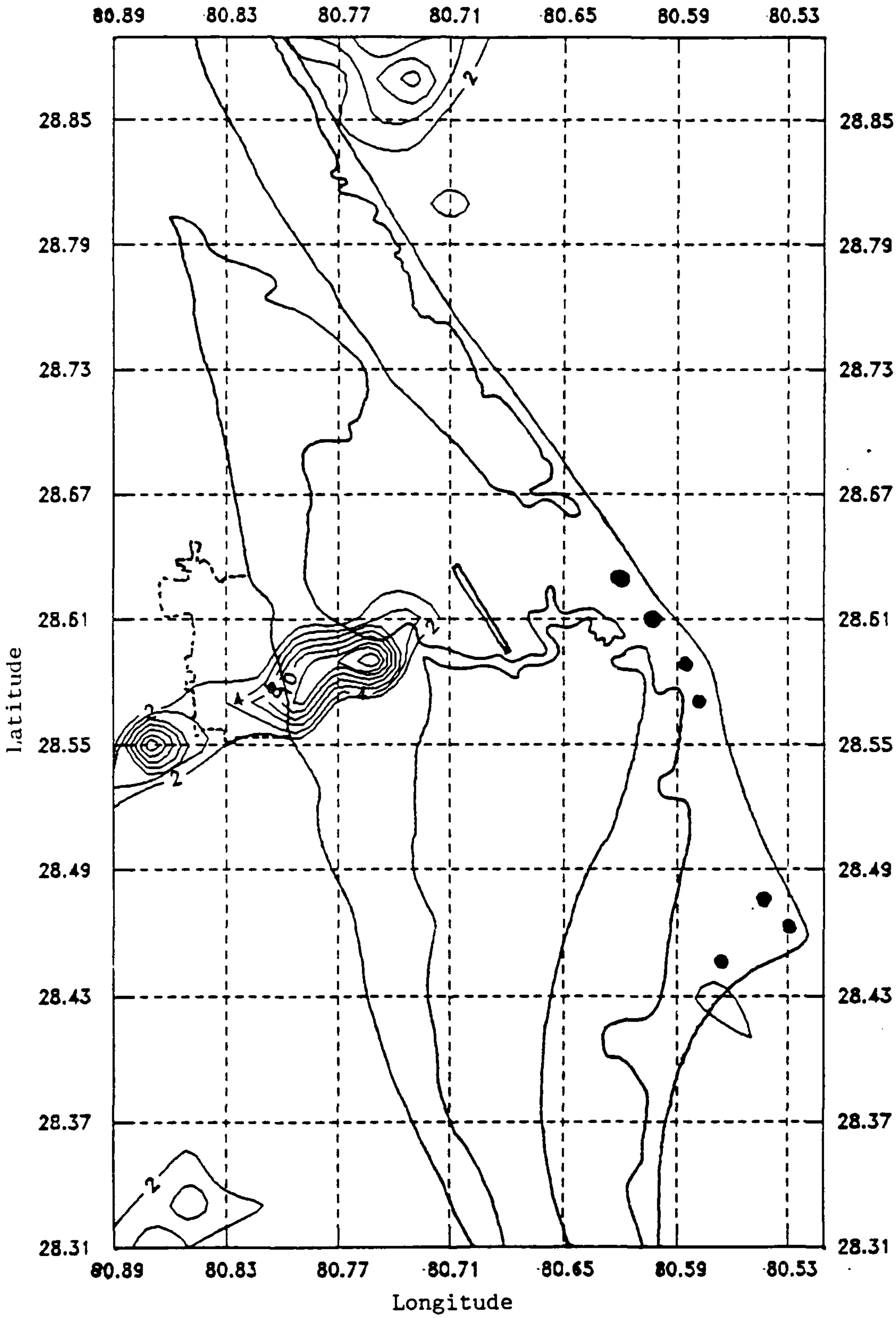

Fig 27. Contours of Cloud-To-Ground Lightning Density on the Cape During 1983 and 1984 (0900 to 1200 EST)

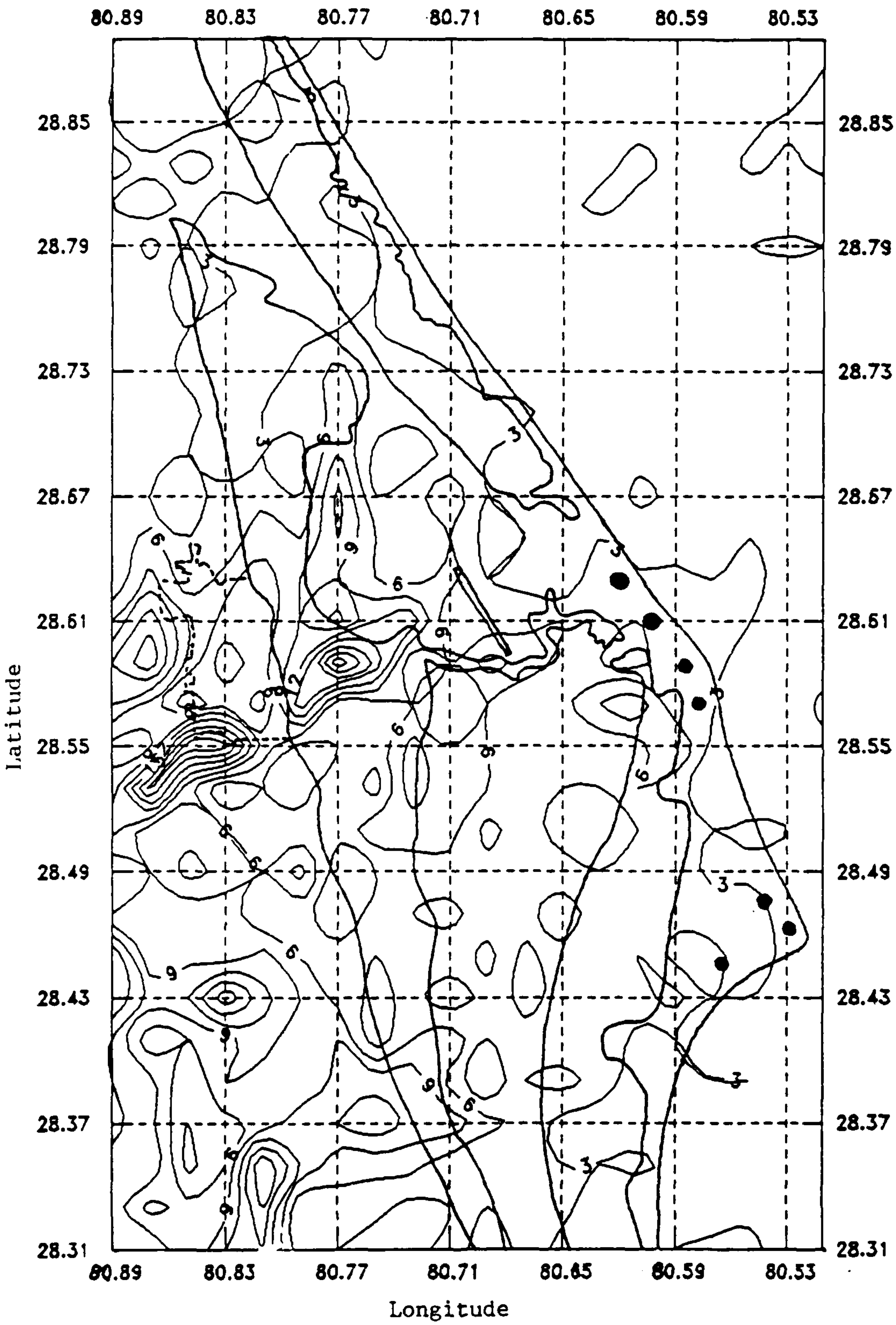

Fig 28. Contours of Cloud-To-Ground Lightning Density on the Cape During 1983 and 1984 (1200 to 1500 EST)

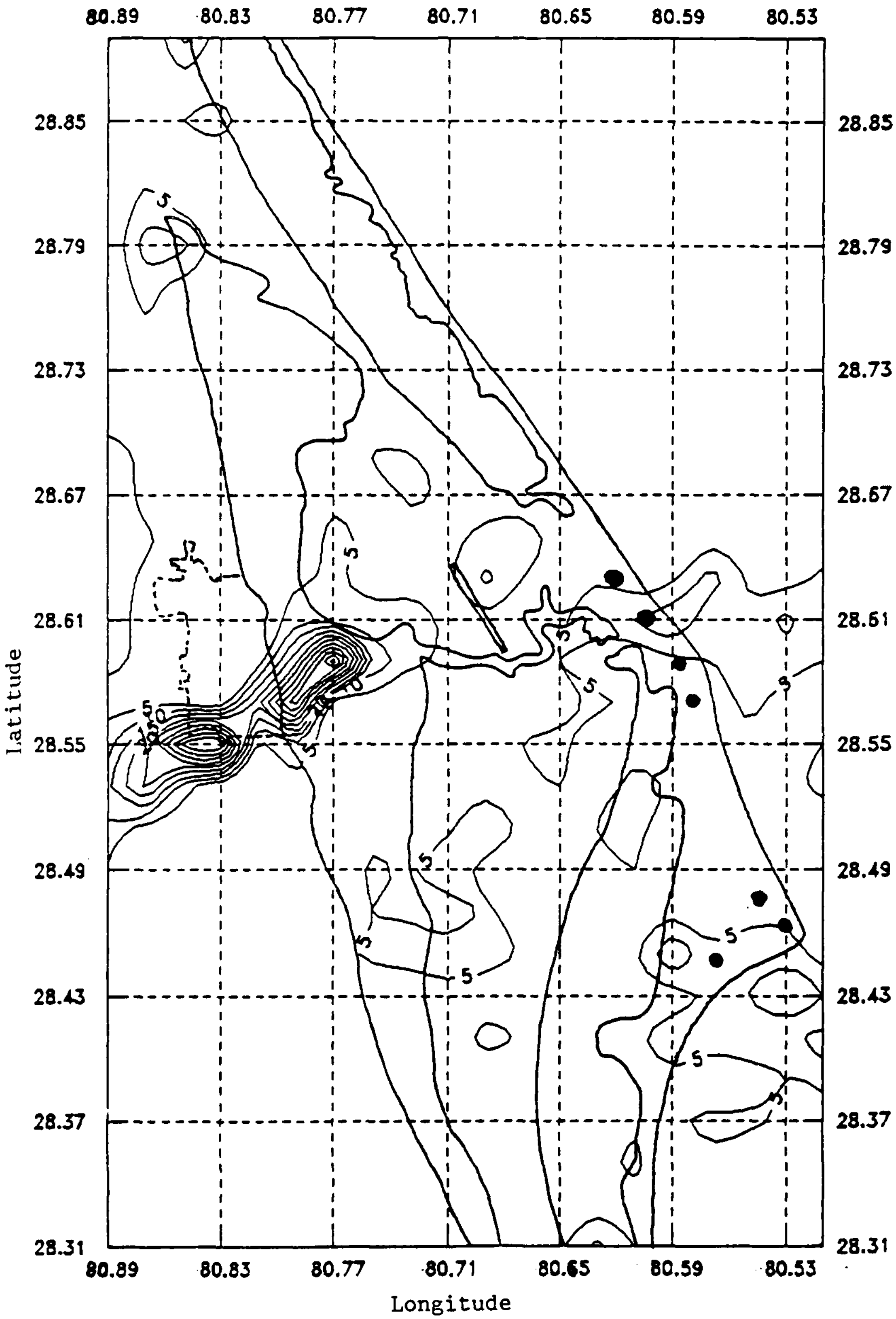

Fig 29. Contours of Cloud-To-Ground Lightning Density on the Cape During 1983 and 1984 (1500 to 1800 EST)

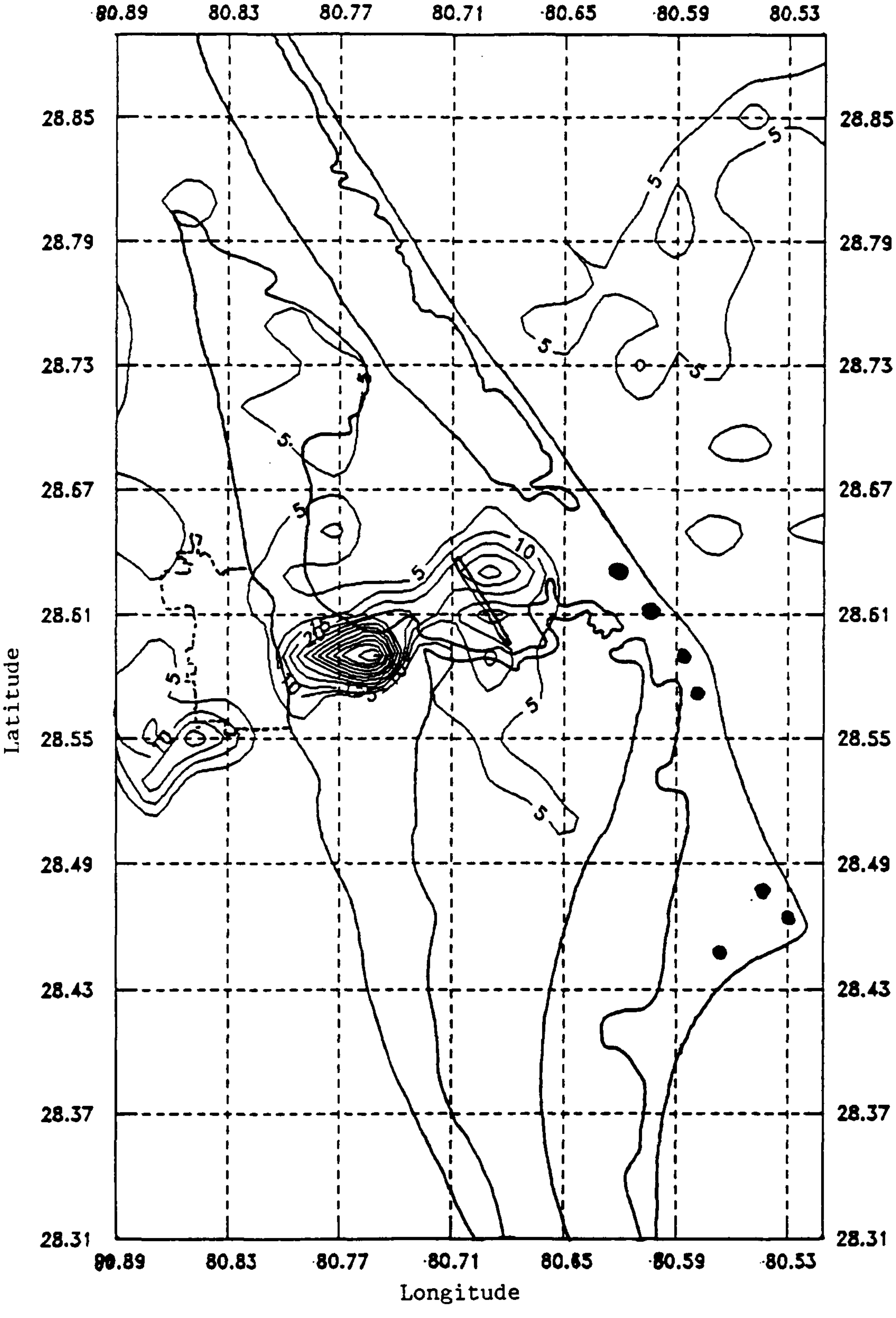

Fig 30. Contours of Cloud-To-Ground Lightning Density on the Cape During 1983 and 1984 (1800 to 2100 EST)

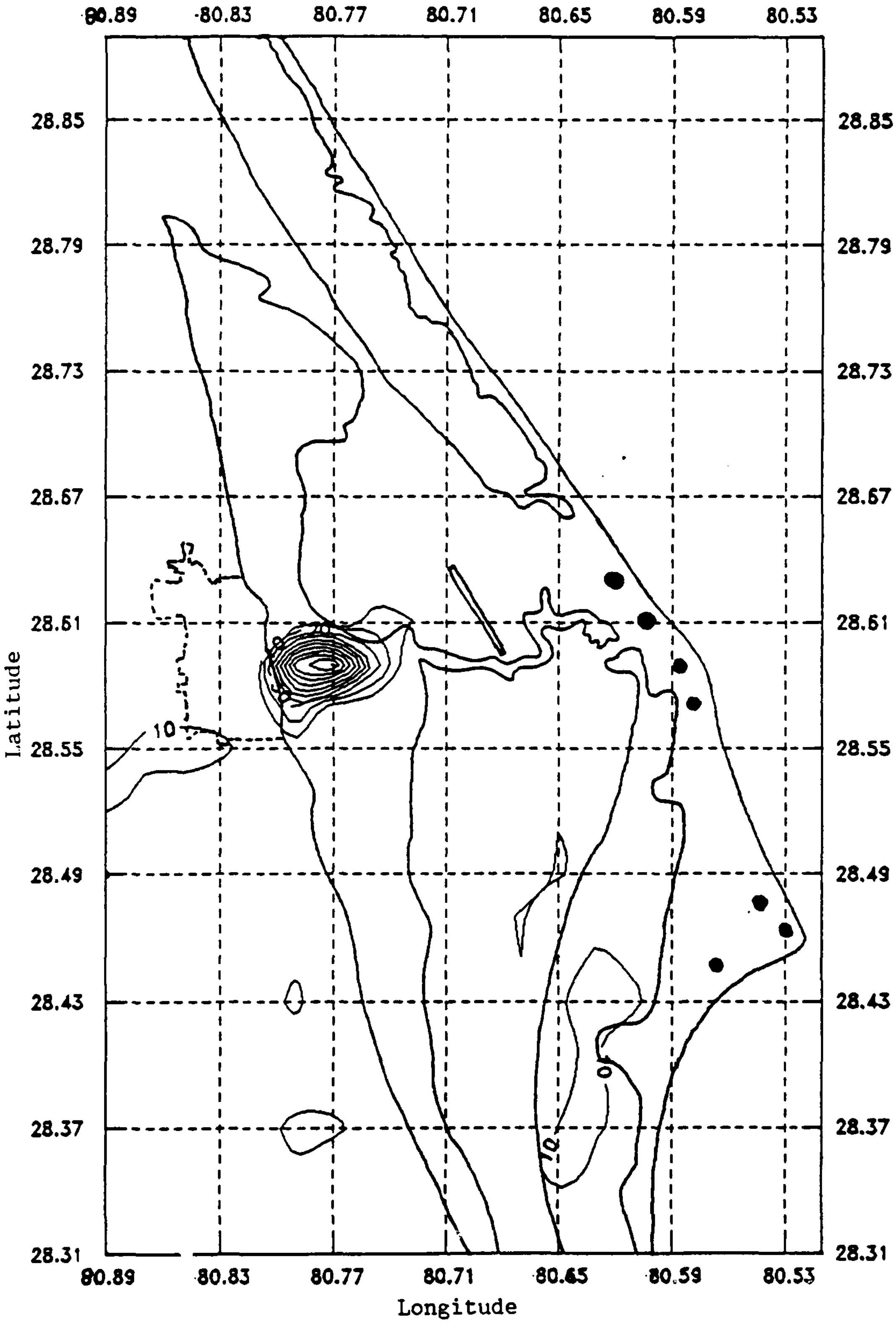

Fig 31. Contours of Cloud-To-Ground Lightning Density on the Cape During 1983 and 1984 (2100 to 2400 EST)

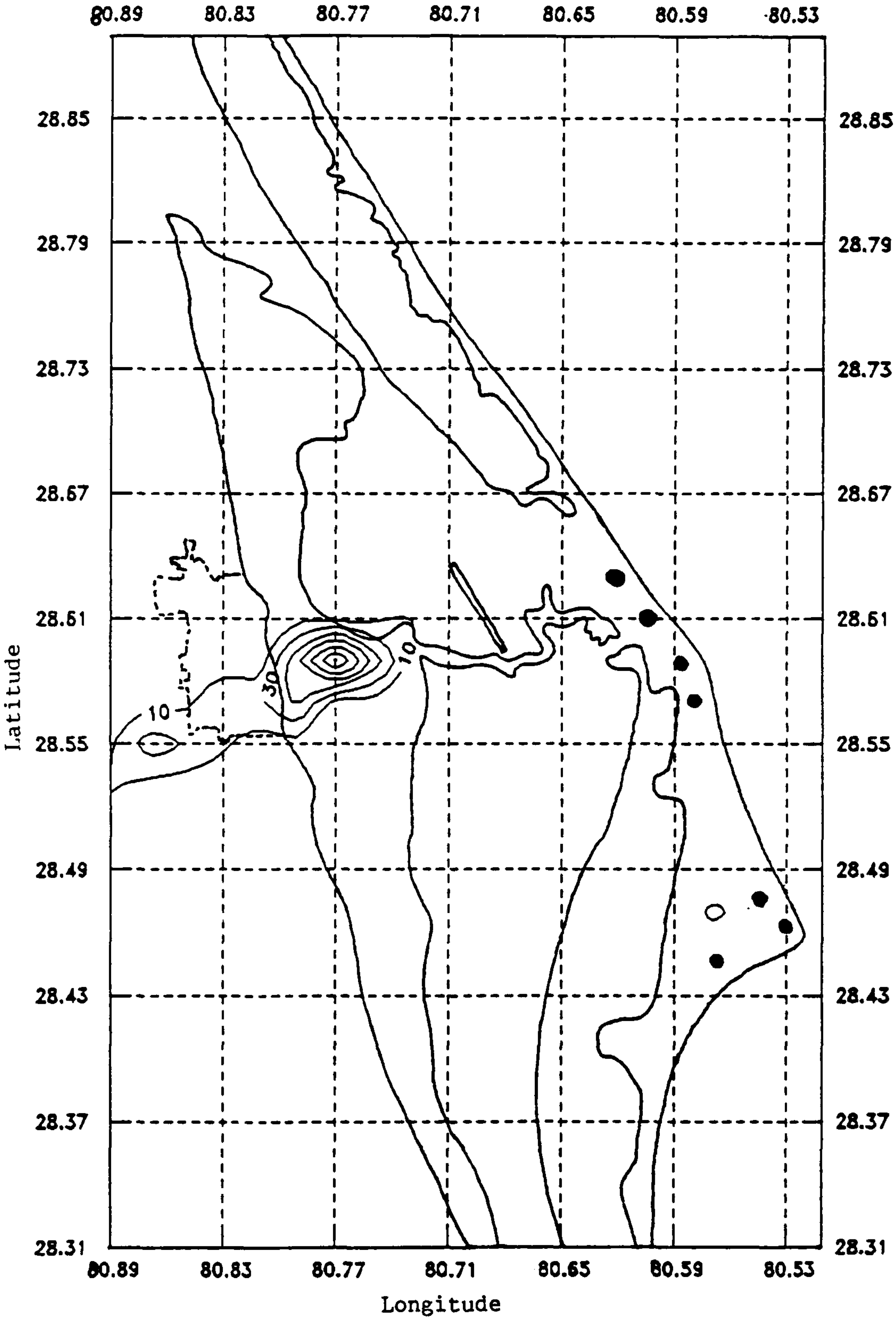

Fig 32. Contours of Cloud-To-Ground Lightning Density on the Cape During 1983 and 1984 (0000 to 1200 EST)

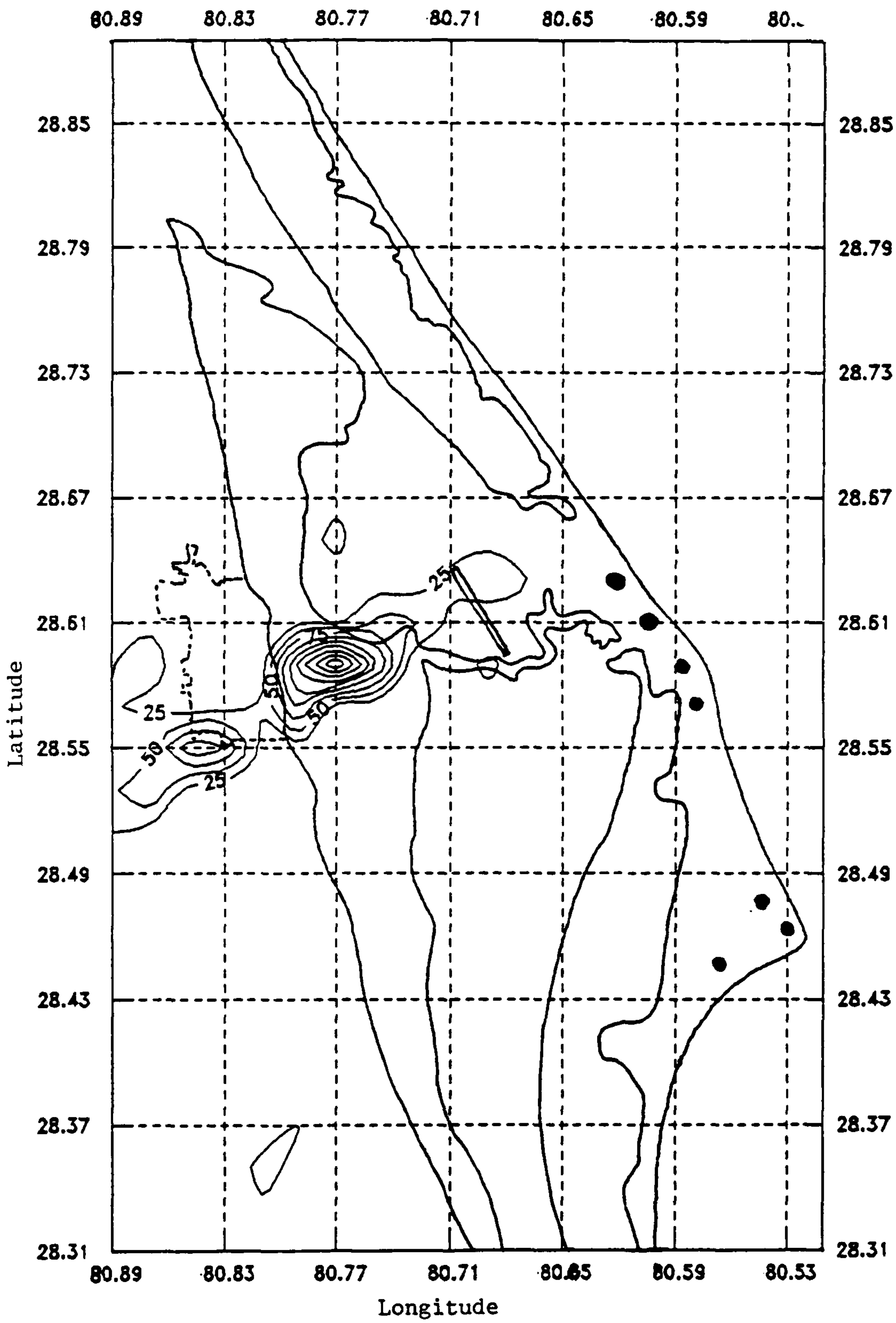

Fig 33. Contours of Cloud-To-Ground Lightning Density on the Cape During 1983 and 1984 (1200 to 2400 EST)

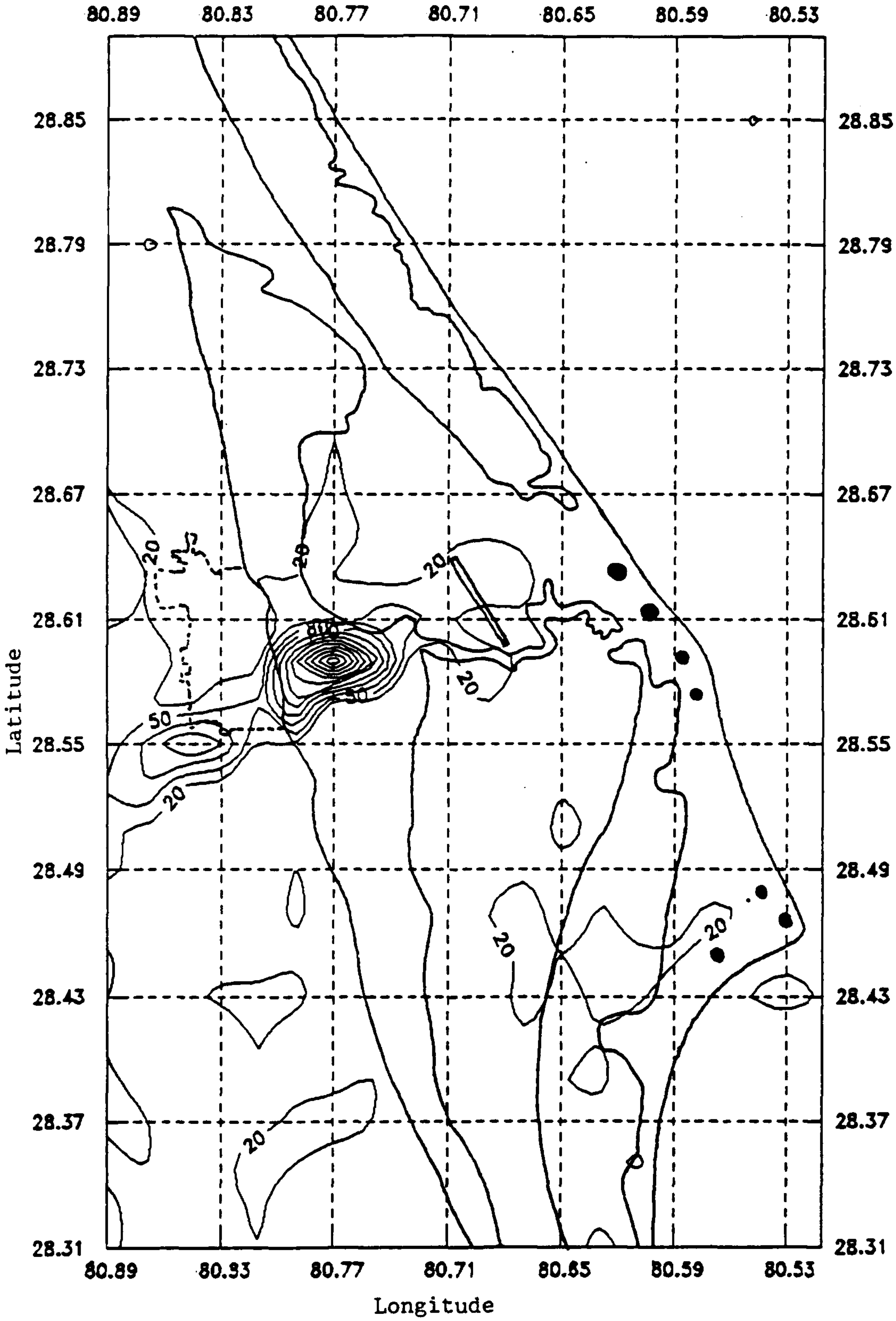

Fig 34. Contours of Cloud-To-Ground Lightning Density on the Cape During 1983 and 1984 (0000 to 2400 EST)

3. The peak density was usually located near 28.59N and 80.77W. This is an area over the Indian River.

4. The high density area was not caused by a single storm. Storms on about forty days over the course of 1983 and 1984 contributed to this area. Approximately 2100 lightning flashes were recorded in the high density area in the two year period. Twenty-three of those storms and 1257 of the flashes were associated with low level winds from the southwest (22:n.p.). Note, the exact numbers here could change, depending on how one chose the area in which to count flashes. I chose the area extending from 28.51N to 28.6N and from 80.72W to 80.9W.

5. This area was less pronounced in 1984. There were only 152 strikes in this area in 1984, compared with 1949 in 1983. In 1984, there was more activity to the south; therefore, this area failed to be so obvious.

Other observations about the spatial distribution must be made with care. Single storms may account for many of the seemingly active areas. For example, from 00-03 (Figure 24), there are several areas contoured which have only 1 to 5 flashes. A single flash, or even 5 flashes over a two year period would not be significant unless that area continued to be more active than its surroundings year after year. We do not yet have the luxury of several years of data. Therefore, only general observations about larger areas can be discussed here.

There is a greater density of lightning over the land during the afternoon. From 12-18 (Figures 28 and 29), there is very little lightning over the Atlantic Ocean. This is not surprising since the land heats up during the day, causing upward vertical motion in the air, and the resulting sea breeze supplies the convergence necessary for air mass thunderstorms over the land.

For this very small area around the Cape, these data show the highest density of lightning to occur over the Atlantic Ocean from 09-12 and 18-21 (Figures 27 and 30). In Figure 27, the lightning over the water is occurring just off the coast on the north side of the Cape.

In general, these findings can be used only to look for areas that will require more analysis in the future. Some interesting patterns were developing in 1983 and 1984. Whether they will continue in the future is yet to be seen.

Launch Availability Based on LLP Data

The first lightning launch constraint dictates that a launch will not occur if lightning has occurred within 10 nautical miles within the past 30 minutes. Using those numbers, how much time would launching have been prohibited in 1983 and 1984? The answer is very different for different sites, months, years, and time of day. The problem is compounded if standoff distances and delay times are also variables.

First, consider the simplest case. Using values from Table 5, the average downtime during the summer for all nine sites mentioned in Chapter 3 is 1.71%. That gives an average launch availability of 98.29% with a standoff distance of 10 nautical miles and delay of 30 minutes.

Table 9 shows the minutes per month of downtime for each site if the downtime is figured separably for each month and each year. These values assume a ten nautical mile standoff and delay time of 30 minutes.

Table 9. Minutes of Downtime for Various Sites During Each Summer Month of 1983 and 1984

MON	YR	PADB	PADA	CX41	CX40	CX36	CX46	CX17	PORT	PAFB
APR	83	1070	1318	1391	1540	1214	1238	1168	912	480
APR	84	218	230	226	226	208	208	208	180	84
MAY	83	212	219	222	224	319	323	315	304	171
MAY	84	338	372	379	379	478	541	460	454	329
JUN	83	1680	1902	2252	2222	2353	2316	2276	2141	1659
JUN	84	108	118	116	116	110	105	110	110	61
JUL	83	3073	2855	2019	1638	472	436	523	518	557
JUL	84	231	348	431	439	724	719	744	636	485
AUG	83	2015	1941	1680	1646	754	704	768	841	606
AUG	84	407	450	517	529	575	606	547	681	701
SEP	83	1169	934	621	533	252	242	256	256	225
SEP	84	525	501	545	541	667	700	642	666	350

From Table 9, the minimum downtime is 61 minutes for Patrick AFB in June 1984 and the maximum is 3073 minutes for Pad 39B in July 1983. As a rule, 1983 experienced more downtime, except in May. Some of the southern sites had more downtime in 1984 than in 1983. Other than for July and August, 1984, the northern most site (Pad 39B) always had more downtime than the southern most site (Patrick AFB).

The average percentage of downtime per month for each site is shown in Table 10. Again, one can see the amount of downtime is a function of month and site. One pattern seems to be the further north the site is, the more downtime it experienced.

Table 10. Average Percentage of Downtime During the Summer for Various Sites

MON	PADB	PADA	CX41	CX40	CX36	CX46	CX17	PORT	PAFB
APR	1.52	1.83	1.91	2.09	1.68	1.71	1.63	1.29	0.67
MAY	0.62	0.66	0.67	0.68	0.89	0.97	0.87	0.85	0.56
JUN	2.11	2.39	2.80	2.76	2.91	2.86	2.82	2.66	2.03
JUL	3.70	3.59	2.74	2.33	1.34	1.29	1.42	1.29	1.17
AUG	2.71	2.68	2.46	2.44	1.49	1.47	1.47	1.70	1.46
SEP	2.00	1.70	1.38	1.27	1.09	1.11	1.06	1.09	0.68

In chapter 3, I showed the effect of increasing the standoff distance from 10 to 20 nautical miles in July. Normally, one might expect that if the radius is doubled, the downtime would quadruple. It is interesting to note that for the two northern sites, Pads A and B, doubling the standoff distance (quadrupling the area) only increased the downtime by factor of less than two. (See Tables 4 and 5 in Chapter 3). For the next two stations south, Complexes 40 and 41, doubling the distance increased the downtime by a factor of about 2.5 times. For the five southern stations, the downtime was increased on the order of 4 to 5 times. The reason for this is the "hot spot" shown in Figures 24 to 34 and discussed earlier in this chapter. A large part of that hot spot is within 10 nautical miles of Pads A and B. Therefore, increasing the standoff distance out to 20 nautical miles did not include much more lightning--they were already being influenced by the high lightning density area. Complexes 40 and 41 were about 11 nautical miles from the center of the eastern lobe of the hot spot. Therefore, they were being affected to a lesser extent at 10 nautical miles, and increasing the standoff distance had a greater impact. The southern stations were 15 to 22 miles from the hot spot. They were unaffected until the radius was increased. Increasing the radius had less impact on Patrick than it did on the other 4 southern sites because the hot spot was about 22 miles from Patrick. If the radius is further increased to 25 nautical miles, the percentage of downtime in July would have increased from 4.3% to 9.92% at Patrick. That more than doubles the downtime, even though the area increases by only 1.56 times. At 25 nautical miles, most of the hot spot is within range of Patrick.

Recall that in 1984, the hot spot was masked by activity just to the south of it. Again, the example in chapter 3 reflects this difference. Much of the lightning in July 1984 was more than 10 nautical miles from Pad B, thus when the radius was increased to 20 nautical miles, the downtime for Pad B increased by 8.81 times. Pad A was closer to the lightning and only increased by 5.93 times. Complexes 40 and 41 were even closer and had increases of about 4 times. The central sites (Complexes 36, 46, and 17) were within 10 miles of most of the lightning in 1984, so increasing the radius had less effect on them. The Port and Patrick were about as far south of the activity as Complexes 40 and 41 were north of it; therefore, they had similar results.

To examine diurnal launch availability changes, I calculated downtimes for Complex 40. The downtimes for Complex 40, based on LLP data, for various standoff distances, delay times, and periods of the day are listed in Appendix B. Figure 18 in Chapter 3 is an example of the data in a further reduced format. In this presentation format, it is easy to see the effect of changing either the delay time or standoff distance or both. Referring to Figure 18, one can see that for a given standoff distance, increasing the delay time has essentially a linear effect on the downtime. However, given a constant delay, the standoff distance appears to increase the downtime exponentially. This is to be expected since changing the delay changes only one dimension--time. When the radius increases, the area increases as the square of the radius. If the lightning events were uniformly distributed in the area, it would be reasonable to suspect that for small delay times, doubling the radius would nearly quadruple the downtime. However, we have already seen that the lightning was not uniformly distributed in 1983 and 1984, and when lightning activity is stratified by 3-hour groups it gets very sparse and detecting patterns becomes very difficult.

Figure 18 contains values derived from 1500-1800 EST in July. That is the period that statistically has the most thunderstorm days. See Table 7. This, then should be the period when launch availability would be most severely affected. However, Figure 18 shows that for a standoff distance of 10 nautical miles and a delay of 30 minutes, the launch availability is 98.1%--greater than the average for the whole month. (Table 10 shows the average downtime for Complex 40 in July was 2.33%). Referring back to Figures 12 and 15 in chapter 3, we see that indeed 1500-1800 EST in July was not a very active period within 20 kilometers (10.8 nautical miles) of Complex 40. Therefore, this result is consistent with the data. Figure 18 also shows there is a rapid decrease in launch availability as the distance increases from 10 to 12.5 nautical miles (Figure 18). This is the range at which the hot spot comes into play.

As mentioned before, downtimes derived from LLP data will tend to be optimistic since LLP only records about 80% of negative cloud-to-ground lightning strikes. Since the model developed in Chapter 4 includes all types of lightning, one would expect the downtimes based on the model to be greater than those based solely on LLP data.

Launch Availability Based on Simulated Data

In Chapter 4, a model was developed to simulate lightning events in the Cape Canaveral area. Those simulated events were analyzed for launch availability. For each summer month and for each 3-hour period of the day in July and August, I found equations that define the amount of downtime to expect for any given standoff distance and delay time. The form of the equation I used was

$$Z = A*R + B*D + C*RR + E*RD + F*DD + G \tag{2}$$

In this section, I list the equations for each of the time periods mentioned above. Figures 35 to 40 are graphs of the projected downtime for each summer month. They are plotted from equations 4 to 9, respectively. Figures 41 to 48 are similar graphs for each 3-hour period of July. They were plotted from equations 10 to 17, respectively. All of these graphs are at the end of this chapter. Graphs are not provided for the 3-hour periods in August, but the equations are listed.

The following equations describe the downtime for each summer month:

$$Z_{APR} = 0.006007*R + .002846*D + .003885*RR + .001496*RD - .000117*DD + .035199 \tag{4}$$

$$Z_{MAY} = 0.037915*R + .006173*D + .006324*RR + .002660*RD - .000212*DD - .146049 \tag{5}$$

$$Z_{JUN} = 0.123836*R + .021862*D + .008267*RR + .003895*RD - .000392*DD - .009275 \tag{6}$$

$$Z_{JUL} = 0.130860*R + .027638*D + .010395*RR + .004269*RD - .000430*DD + .151971 \tag{7}$$

$$Z_{AUG} = 0.084771*R + .019183*D + .012297*RR + .004639*RD - .000432*DD - .216826 \tag{8}$$

$$Z_{SEP} = 0.086027*R + .009749*D + .007737*RR + .003863*RD - .000318*DD - .291602 \tag{9}$$

All of these equations were derived from 100 discrete values of downtime for 10 different standoff distances (from 3 to 30 nautical miles) and 10 delay times (from 6 to 60 minutes). In every case, the R-square was greater than 0.98, which means that the equation model accounts for at least 98% of the variability in the data. The equations fit the data points very well for the ranges where data points were calculated; however, the equations should not be used for extrapolation outside those ranges.

The equations that define downtime for each 3-hour period in July are:

$$P1J = -.171903*R - .023551*D + .007445*RR + .003761*RD + .000114*DD + 1.295071 \tag{10}$$

$$P2J = -.062705*R - .000431*D + .002615*RR + .000467*RD - .000035*DD + .264959 \tag{11}$$

$$P3J = -.045036*R - .005157*D + .004244*RR + .001793*RD - .000085*DD + .177063 \tag{12}$$

$$P4J = -.268132*R + .006233*D + .015979*RR + .004228*RD - .000497*DD + 1.289937 \tag{13}$$

$$P5J = -.033320*R + .021883*D + .026908*RR + .013380*RD - .001046*DD + .745478 \tag{14}$$

$$P6J = 0.228835*R + .029961*D + .026979*RR + .022537*RD - .000957*DD + .000883 \quad (15)$$

$$P7J = -.535321*R - .033831*D + .039430*RR + .019644*RD - .000424*DD + 3.751337 \quad (16)$$

$$P8J = -.180066*R - .052445*D + .015368*RR + .011431*RD + .000039*DD + 1.494308 \quad (17)$$

Where P1J is the percentage of downtime for the first period (0000-0300 Local Standard Time) in July; P2J is for 0300-0600, etc.

The equations that define the downtime for 3-hour periods in August:

$$P1A = -.063003*R - .004432*D + .005226*RR + .002830*RD - .000056*DD + .627563 \quad (18)$$

$$P2A = -.007590*R - .003371*D + .004593*RR + .003573*RD - .000103*DD + .325887 \quad (19)$$

$$P3A = -.051242*R + .001072*D + .005047*RR + .003059*RD - .000194*DD + .368748 \quad (20)$$

$$P4A = 0.002320*R + .007269*D + .011086*RR + .005816*RD - .000410*DD - .211319 \quad (21)$$

$$P5A = 0.041354*R - .013313*D + .023374*RR + .013697*RD - .000591*DD - .013760 \quad (22)$$

$$P6A = -.001217*R - .010519*D + .034426*RR + .023220*RD - .000911*DD + .953059 \quad (23)$$

$$P7A = -.178\text{[illegible]}94*R - .040915*D + .025564*RR + .019290*RD - .000301*DD + 2.026989 \qquad (24)$$

$$P8A = 0.194820*R - .034594*D + .002072*RR + .009655*RD + .000103*DD - .465949 \qquad (25)$$

Where P1A is the percentage of downtime for the first period (0000-0300 Local Standard Time) in August.

Each of the 3-hour equations also has a high R-square. However, the R-square for P2J is only 0.963. This is understandable since there are so few storms during that period of the day. Fewer observations make it possible for one particularly large storm or a particularly quiet year to skew the data. Still, that equation represents the data well, and all the equations describe the downtime based on the simulation model very well.

The downtimes based on the simulated data are indeed larger than those based solely on LLP data but match very well. For example, in June, the downtime for complex 40 was 2.76% based on LLP data (Table 10). Based on the simulated data (using equation (6)), the downtime for June is 3.53%.

The expected differences are greater when comparing 3-hour groups, since the delay time, e.g., 30 minutes, is a larger percentage of the total time for a 3-hour group than for a monthly group. The month of July has 744 hours, but each 3-hour group in July has only 93 hours. Also, the diurnal extremes are not smoothed for the 3-hour groups as they are in monthly groups. From Table 11 in Appendix B, the downtime would have been 1.9% for July from 15-18 LST, based on LLP data with a standoff of 10 nautical miles and a delay time of 30 minutes. Based on the simulated data and equation (15), the downtime for that period is 11.5%.

There are two reasons for this large difference. First, Complex 40 is not within 10 nautical miles of the hot spot discussed earlier. If the standoff distance is increased just 2.5 nautical miles, the downtime based on LLP data increases to 4.5% (Figure 18), while the downtime based on simulated data increases to 15.5% (Equation 15). Furthermore, July experienced less lightning within 20 kilometers of Complex 40 in both 1983 and 1984 than the model predicts. See Figure 12. Even more significant, Figure 15 shows the amount of lightning within 20 kilometers of Complex 40 from 1500 to 1800 LST in July is EXTREMELY low.

It is important to realize that even if a model is correct, it only provides approximate answers--and in the case of the model in this thesis, it only looks for average values. Extremes in the weather can depart from those averages significantly.

Overall, I believe the model does a very good job of showing the trends in launch availability if standoff distances and/or delay times are changed. Of course, the model does not use the spatial distribution of lightning that was found using the LLP data. If more data is analyzed and it shows there is a pattern that can be modelled, that pattern should be used in the model.

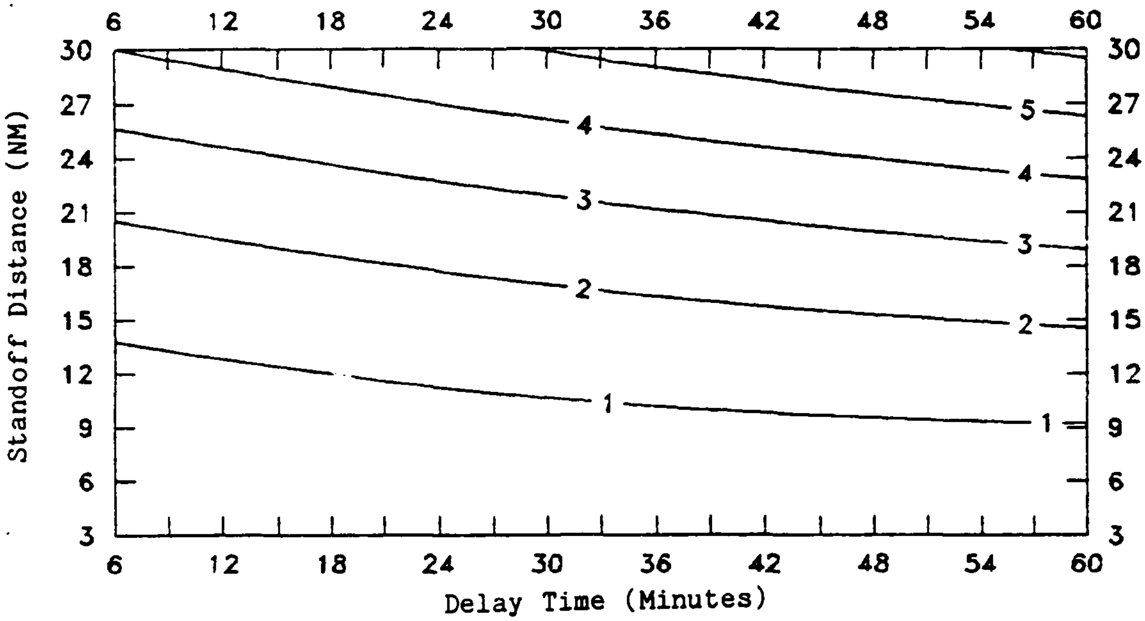

Fig 35. Percentage of Lost Launch Availability in April as a function of Standoff Distance and Delay Time (Based on Simulated Data)

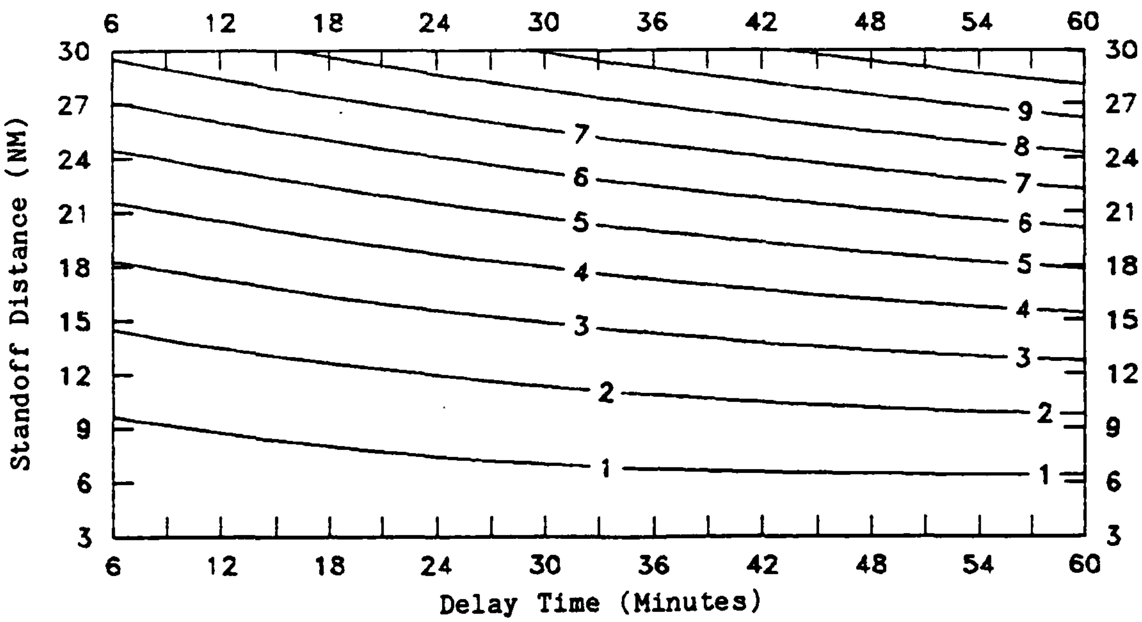

Fig 36. Percentage of Lost Launch Availability in May as a function of Standoff Distance and Delay Time (Based on Simulated Data)

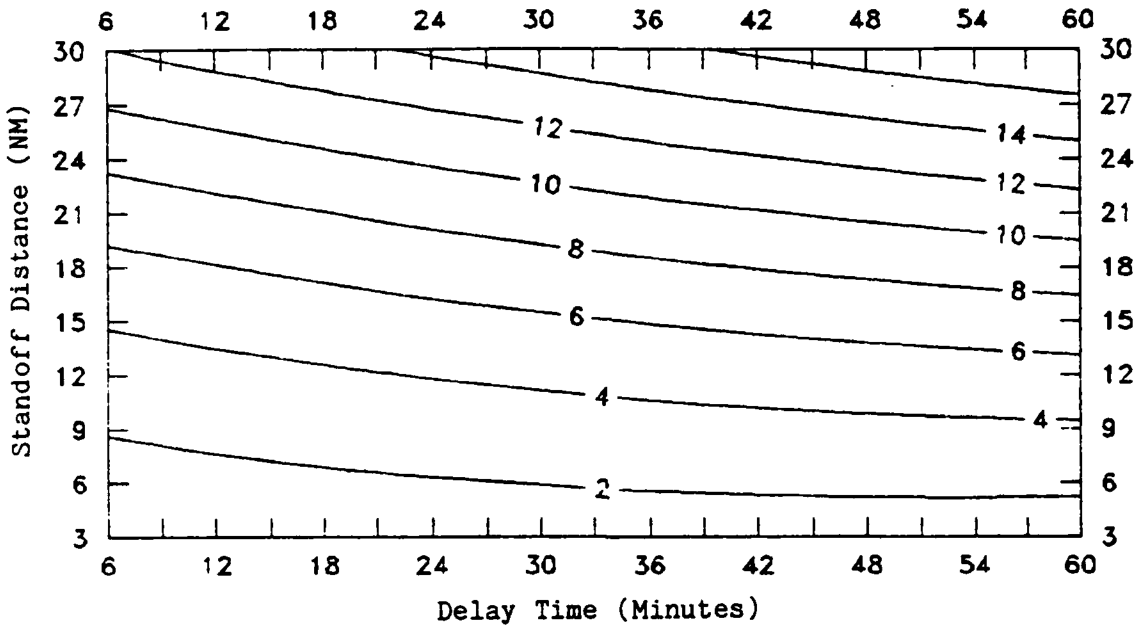

Fig 37. Percentage of Lost Launch Availability in June as a function of Standoff Distance and Delay Time (Based on Simulated Data)

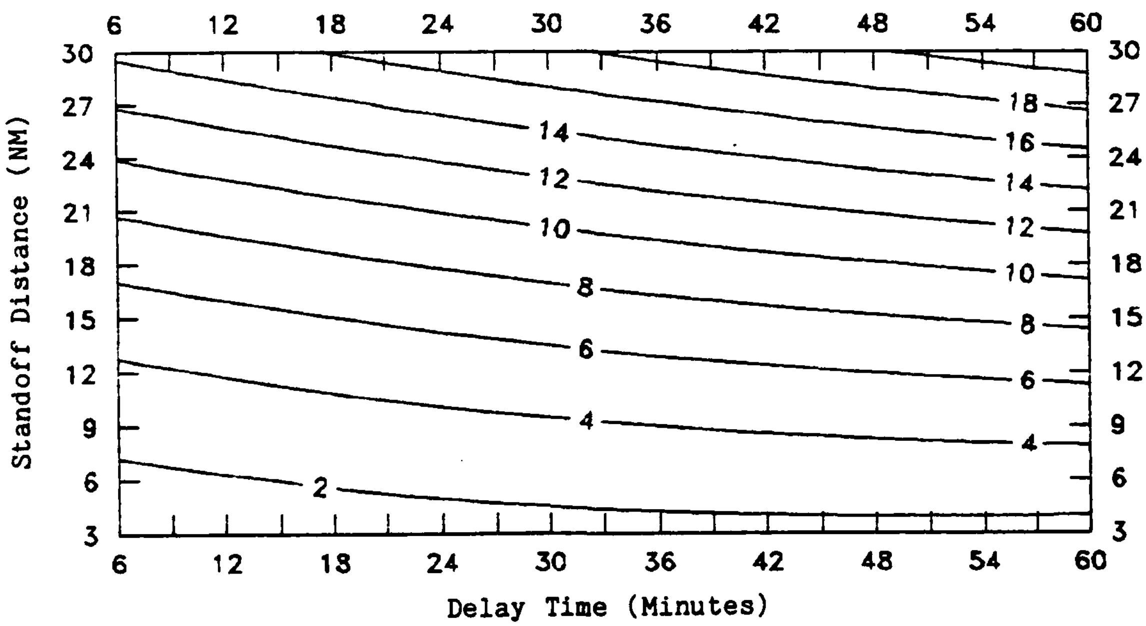

Fig 38. Percentage of Lost Launch Availability in July as a function of Standoff Distance and Delay Time (Based on Simulated Data)

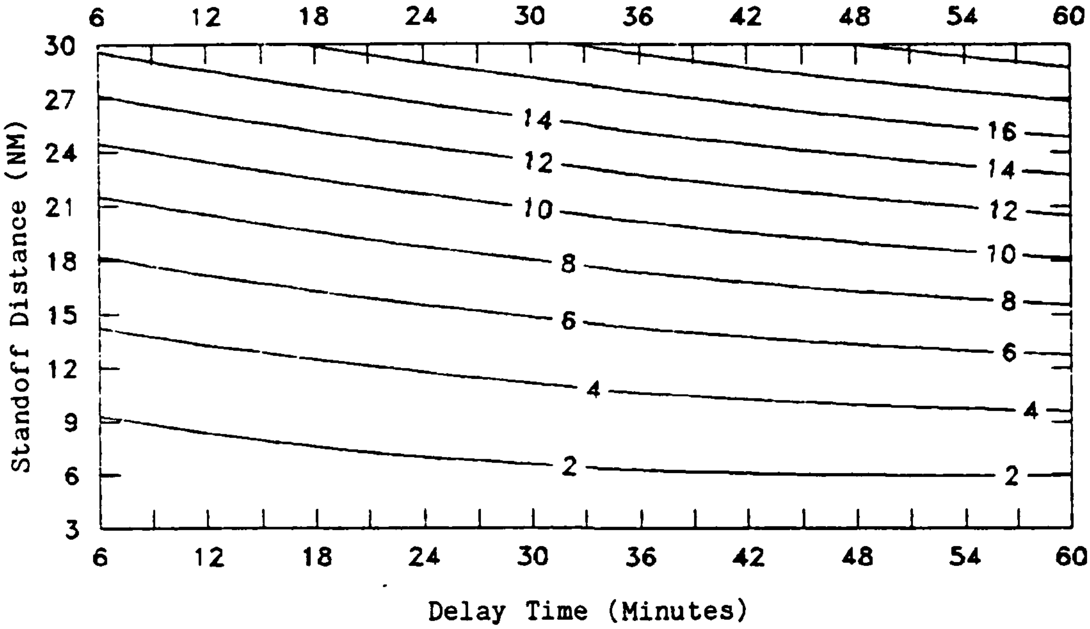

Fig 39. Percentage of Lost Launch Availability in August as a function of Standoff Distance and Delay Time (Based on Simulated Data)

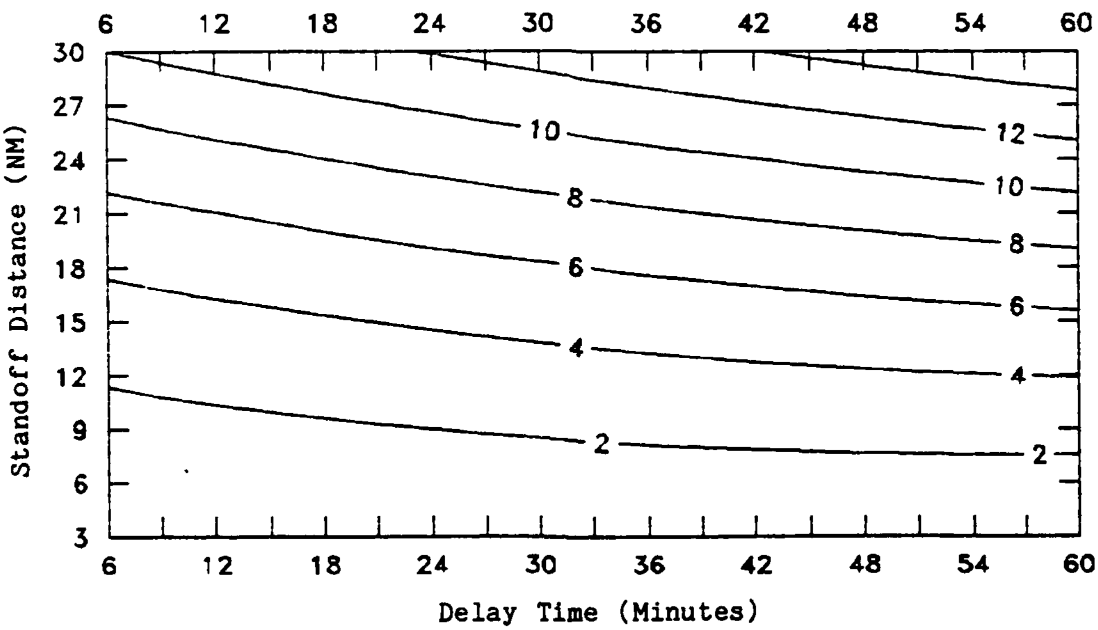

Fig 40. Percentage of Lost Launch Availability in September as a Function of Standoff Distance and Delay Time (Based on Simulated Data)

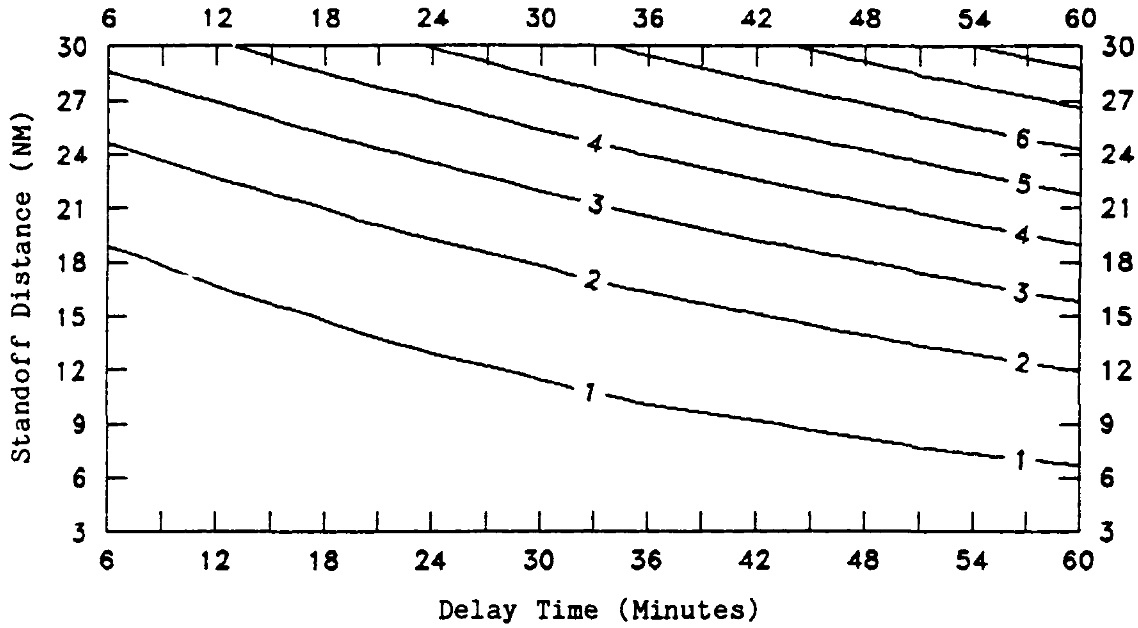

Fig 41. Percentage of Lost Launch Availability in July from 0000 to 0300 EST as a Function of Standoff Distance and Delay Time (Based on Simulated Data)

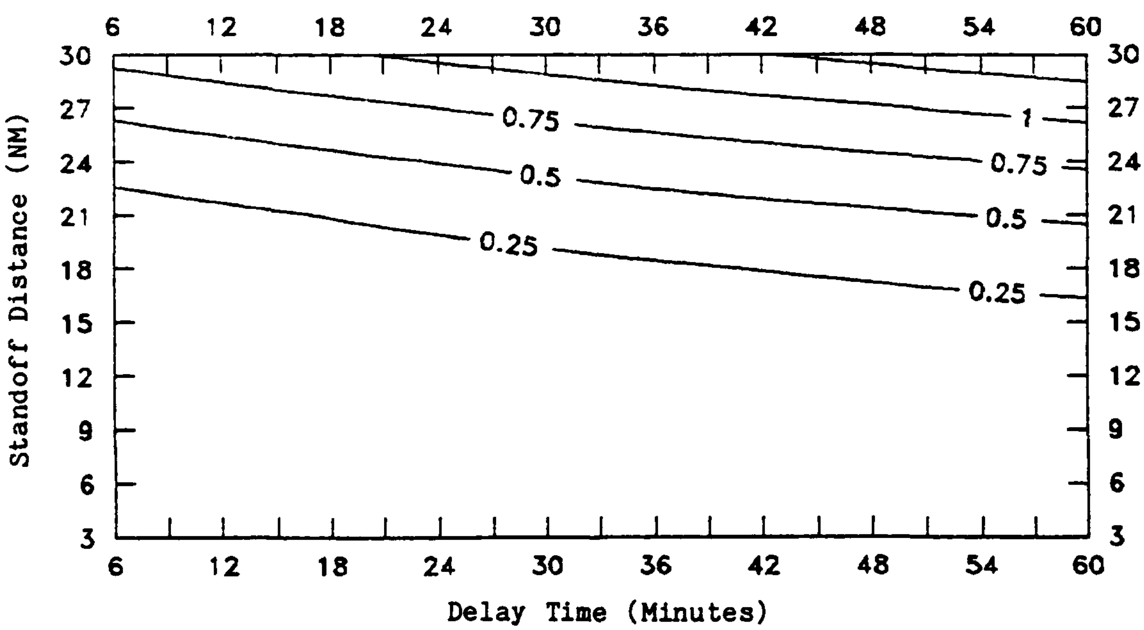

Fig 42. Percentage of Lost Launch Availability in July from 0300 to 0600 EST as a Function of Standoff Distance and Delay Time (Based on Simulated Data)

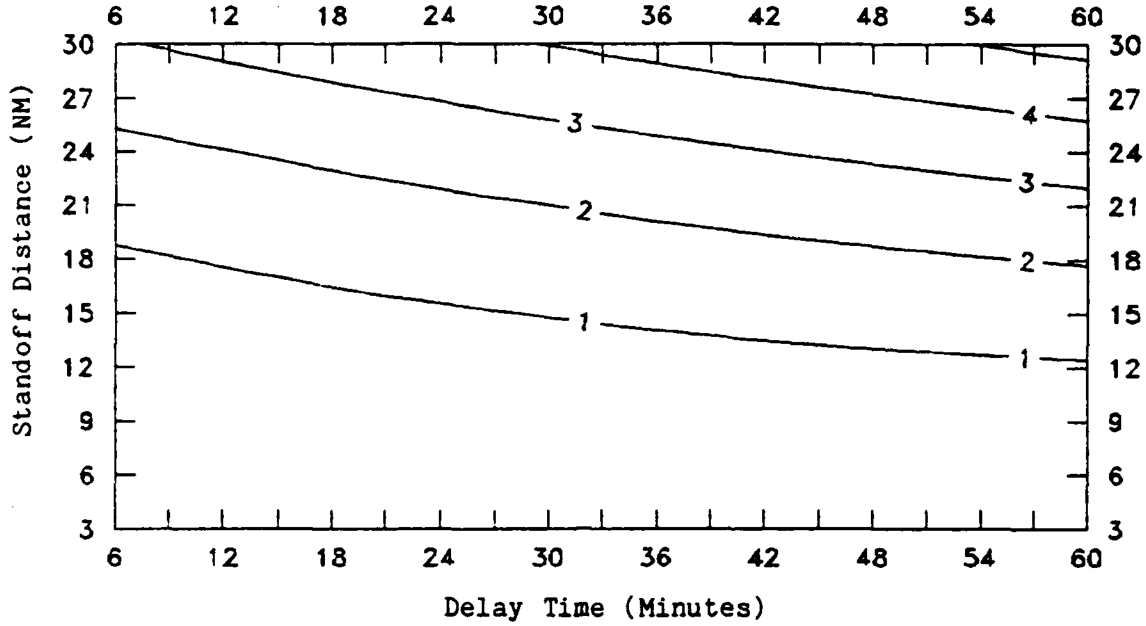

Fig 43. Percentage of Lost Launch Availability in July from 0600 to 0900 EST as a Function of Standoff Distance and Delay Time (Based on Simulated Data)

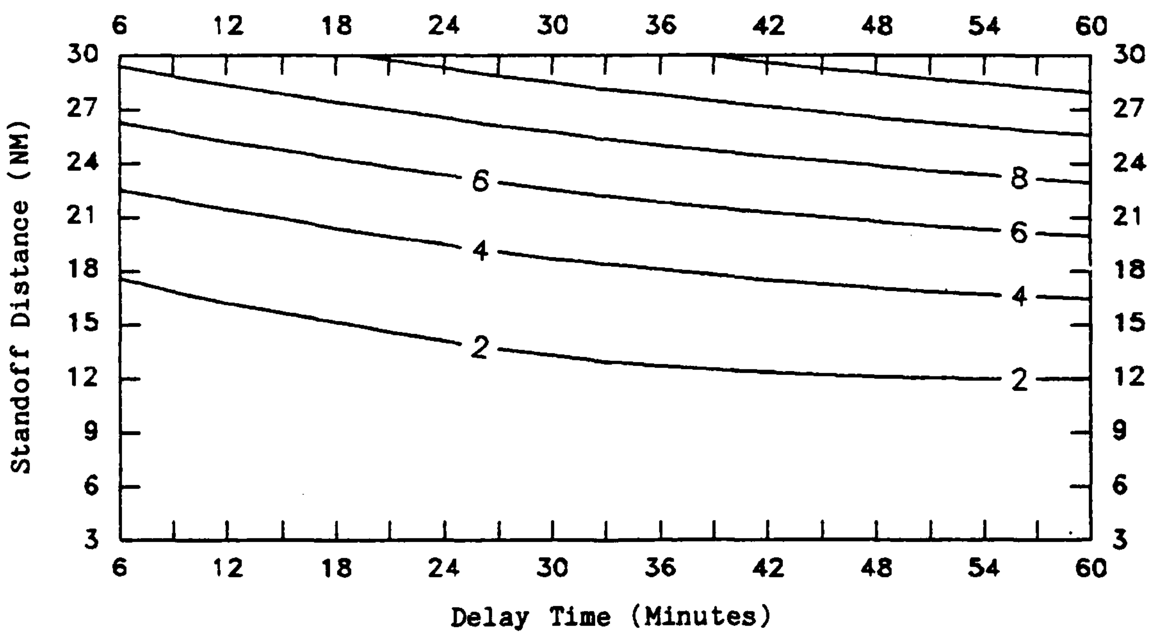

Fig 44. Percentage of Lost Launch Availability in July from 0900 to 1200 EST as a Function of Standoff Distance and Delay Time (Based on Simulated Data)

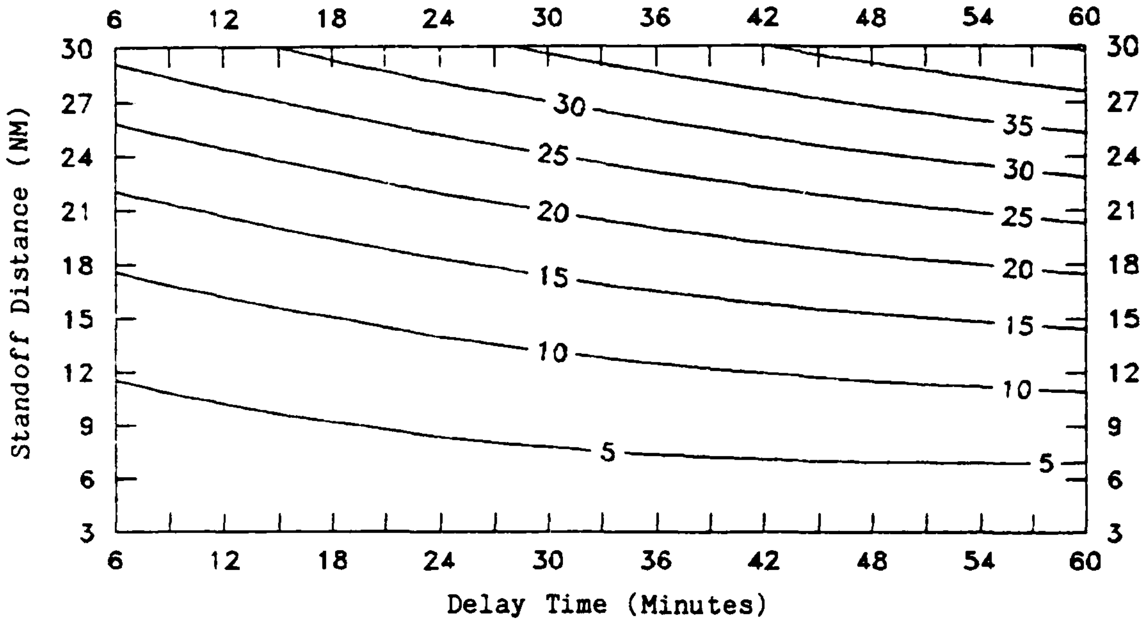

Fig 45. Percentage of Lost Launch Availability in July from 1200 to 1500 EST as a Function of Standoff Distance and Delay Time (Based on Simulated Data)

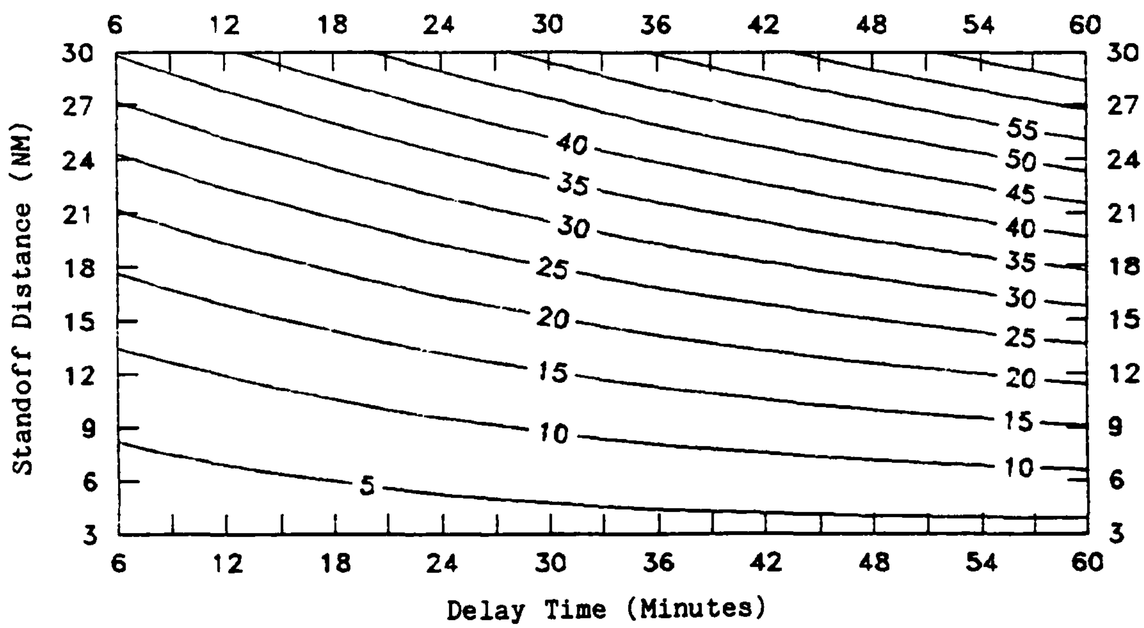

Fig 46. Percentage of Lost Launch Availability in July from 1500 to 1800 EST as a Function of Standoff Distance and Delay Time (Based on Simulated Data)

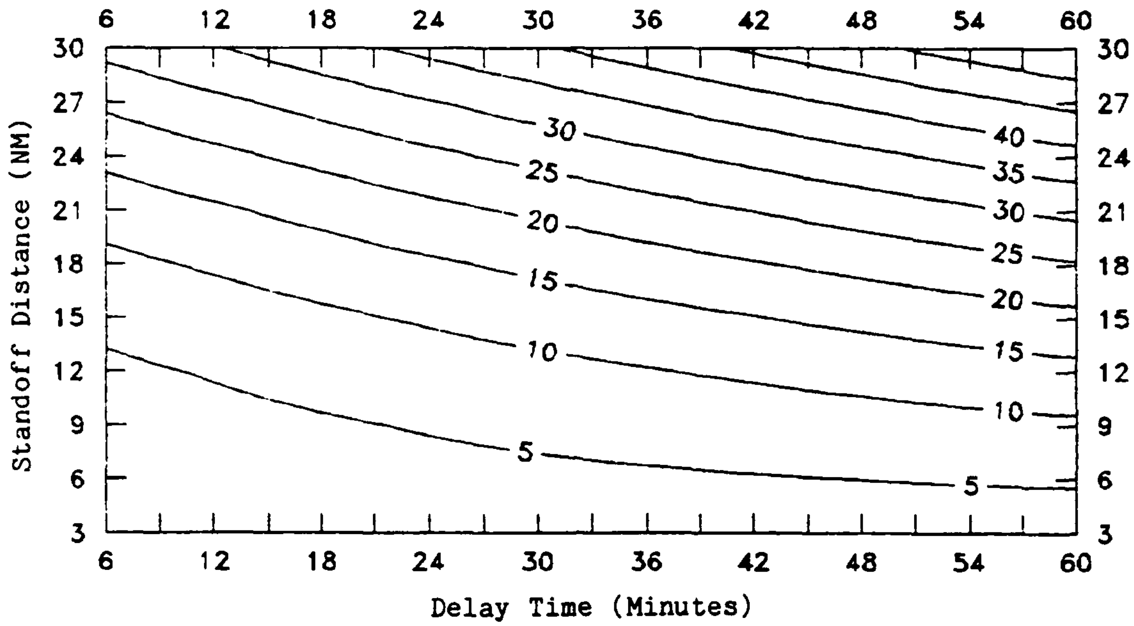

Fig 47. Percentage of Lost Launch Availability in July from 1800 to 2100 EST as a Function of Standoff Distance and Delay Time (Based on Simulated Data)

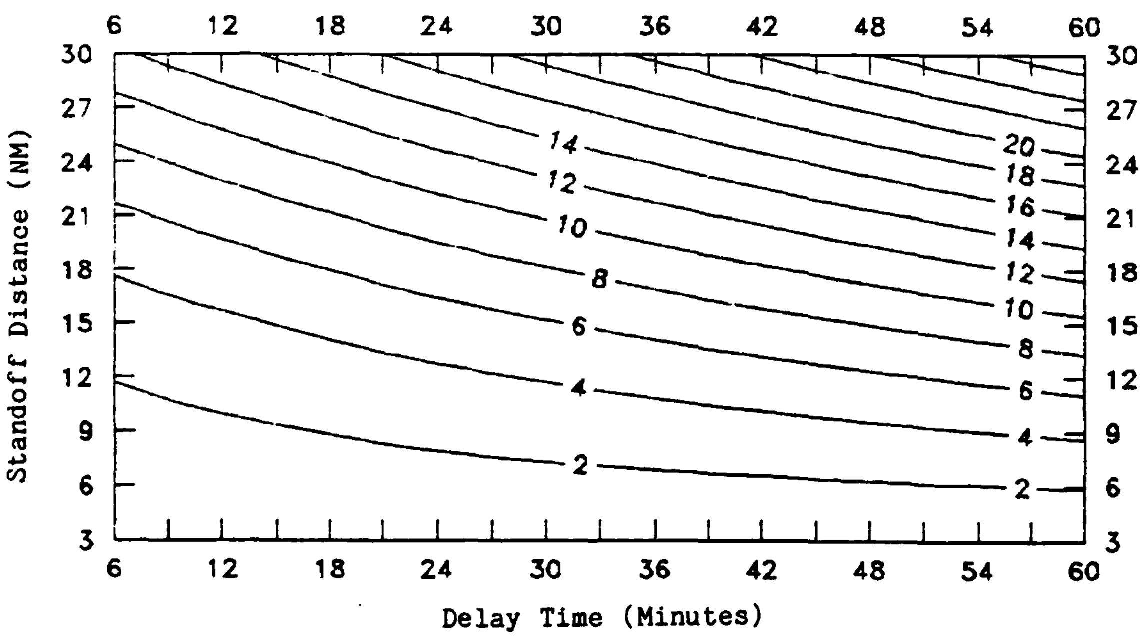

Fig 48. Percentage of Lost Launch Availability in July from 2100 to 2400 EST as a Function of Standoff Distance and Delay Time (Based on Simulated Data)

VI. Summary and Suggestions for Future Research

This thesis covered 3 main areas. First, the background of triggered lightning as it pertains to aerospace vehicles was covered. That included reviewing the current knowledge of triggered lightning, and how lightning launch constraints have been developed to deal with the problem. I reviewed each of the current constraints and the equipment used to evaluate whether or not the constraint is violated.

The second section was an analysis of a 1983 and 1984 cloud-to-ground lightning set. I examined the spatial and diurnal distributions of lightning around Cape Canaveral and found that lightning is not uniformly distributed over the area. Rather, lightning density was greater on the West side of the Cape, with a peak density (hot spot) just West of the Shuttle Landing Facility. Activity in this area was usually associated with low-level winds from the southwest.

I also used the lightning data set to evaluate the impact that lightning would have had on launch availability in 1983 and 1984, and found that for a given standoff distance and delay time, the launch availability (based on the first constraint only) was a function of launch site location, time of year, and time of day. Generally, the northern launch sites experienced greater loss of launch availability than the southern sites, but the most important factor was the distance that the site was from the hot spot. As would be expected, launch availability decreased in July and August and in the afternoons when thunderstorms are more prevalent in Central Florida.

To evaluate the impact of all types of lightning (in-cloud and cloud-to-cloud as well as cloud-to-ground), I developed a lightning simulation model in the third major section. The model simulates time and location of lightning events around the Cape. I analyzed that data to determine launch availabilities given various standoff distances and delay times. I then developed continuous equations that describe percentage of lost launch availability for each summer month (April to September) and for each 3-hour period of the day in July and August. Several of those equations were graphed and presented as a set of curves describing percentages of downtime.

There are several areas that need further research in each of the sections this thesis covered. A full analysis of the lightning launch constraints needs to be done to answer the questions in Chapter 1:

a. Do the constraints define the conditions that constitute a triggered lightning threat to aerospace systems?

b. What impact do the constraints have on launch availability?

c. How representative of the electric field aloft are the parameters that can be measured on the ground?

d. What impact would the use of an airborne electric field mill system have on adherence to the constraints?

e. Which constraints will delay launching the most, and should they be modified?

f. What other parameters might be important that are not addressed by the constraints?

All of these questions are still open to research. Also, as mentioned in the text, the exhaust plume of rockets need to be studied more to determine whether or not it is a factor in triggered lightning.

When more lightning data are available, a more in-depth analysis of the spatial distribution of lightning as a function of time needs to be done. The evidence from 1983 and 1984 is that there are certain geographic locations where lightning is more frequent. Land/water interfaces, land/sea breezes, convergence, divergence, and prevailing low-level winds have impacts on thunderstorm development and position. The correlation between these factors and the position, frequency, and severity of thunderstorms would be a very useful forecasting tool.

Many times while I was working on the simulation model, I realized that more research was needed to attain more accuracy for the distributions used in the model. If the probabilistic location, duration, flash rate and size of a storm could be solved as a function of time, those distributions could easily be used in the model. Perhaps the distribution of the LLP lightning data could be used to help solve part of the spatial distribution problem. Further refinements of the expected frequency of storms as a function of time would also help the model produce more accurate results.

Appendix A: LLP Theory

This appendix gives a brief description of the LLP direction finder (DF) theory. The interested reader should refer to Krider and Noggle (17:301-306) and Maier, et al (28:497-504), for more details on the history and electronics of the LLP direction finder.

There is a magnetic field associated with lightning discharges. That field propagates radially outward from the flash. If the magnetic field encounters two orthogonal magnetic loop antennae, the ratio of the voltages in the loops can be used to determine the direction to the source of the lightning flash. For example, in Figure 49, the crossed loop antennae are represented by "NS" (North-South) and "EW" (East-West). "MF" is the magnetic field that crosses the antennae. "a" is the angle between the direction of motion of the magnetic field and the plane of the NS antenna. Similarly, "b" is the angle between the direction of field and the plane of the EW antenna. The voltage observed by each antenna is proportional to the strength of the magnetic field and the cosine of the angle between the antenna and the direction of motion of the field.

$$V_{NS} = C * MF * \cos(a) \tag{26}$$

$$V_{EW} = C * MF * \cos(b) \tag{27}$$

Where V is the voltage, and C is a constant determined by the electronics of the DF, and the other variables are defined above.

The voltage ratio, R, is

$$R = V_{NS}/V_{EW} = \cos(a)/\cos(b) \tag{28}$$

Also,

$$a + b = 90 \text{ degrees} \tag{29}$$

Therefore,

$$a = 90 - b \tag{30}$$

$$\cos(a) = \cos(90-b) = \sin(b) \tag{31}$$

Substituting (31) into (28),

$$R = \sin(b)/\cos(b) = \tan(b) \tag{32}$$

and

$$b = \text{ArcTan}(R) \tag{33}$$

All this tells us, though, is that the magnetic field came from a bering of b degrees or b+180 degrees. There is an ambiguity in the direction, and no information concerning the range to the flash. To solve this problem, two direction finders are placed several kilometers apart. Figure 50 illustrates how two DFs could locate a distant lightning flash by triangulation.

Another problem arises if the flash is too near the baseline between A and B (Figure 51). Obviously, *triangulation would not work* if the flash were right on the baseline. Therefore, if possible, a third DF is used to solve the problem as shown in Figure 51.

All of the information collected by the DFs are fed into a position analyzer which is preprogrammed to compute, map, and record lightning locations. The position analyzer then sends the location to the user in real time.

Site Errors

Site errors are caused by uneven terrain, power lines, or other conducting surfaces near a direction finder. "For example, a nearby overhead electric power line can act as a large antenna loop and can re-radiate a small portion of the lightning magnetic field and cause an

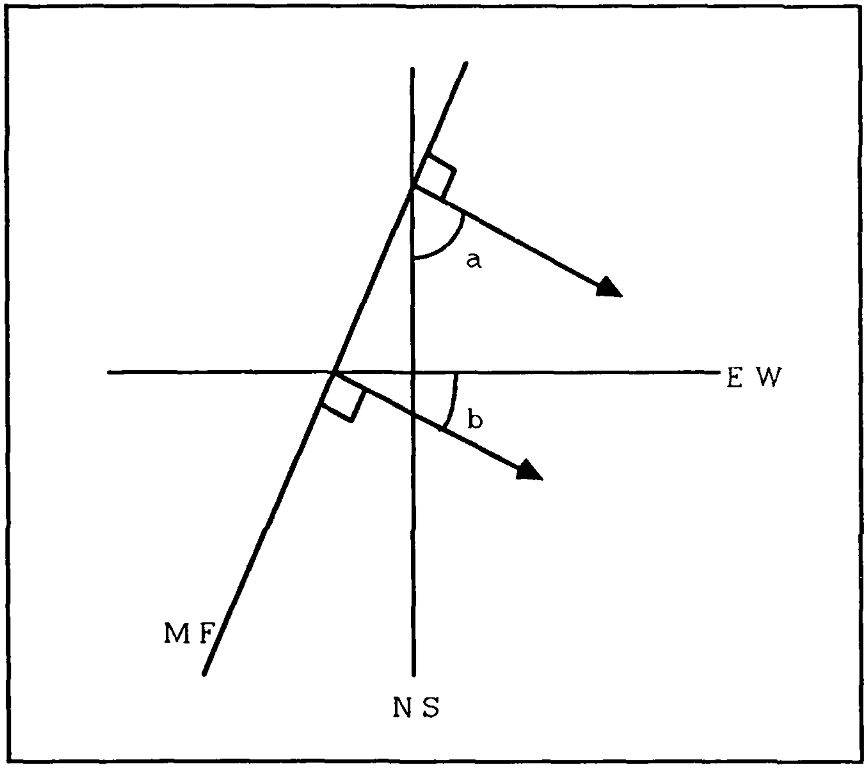

Fig 49. Diagram of Magnetic Field Wave Front (MF) Encountering Orthogonal Loop Antennae (NS) and (EW)

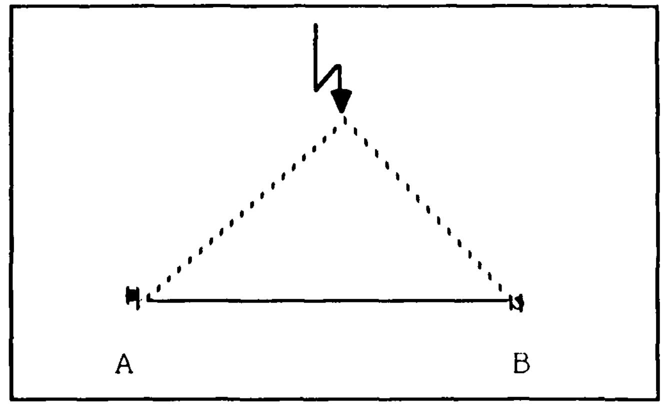

Fig 50. Illustration of Two Direction Finders and Triangulation

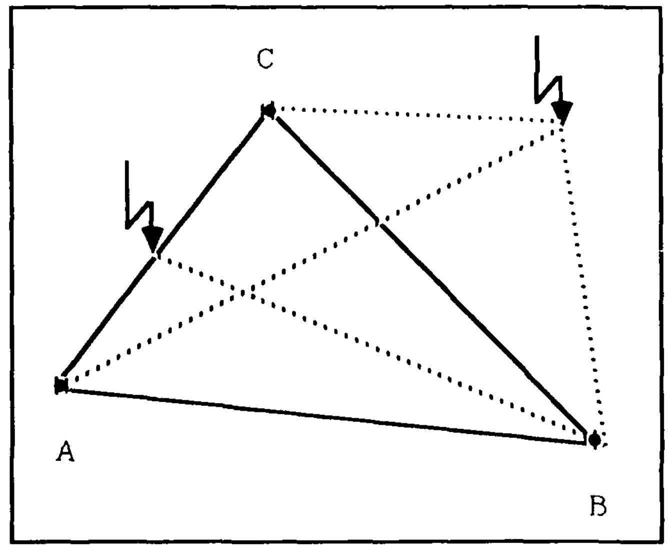

Fig 51. Illustration of Three Direction Finders and Removal of Base Line Ambiguity

angle error" (28:501). If an ideal site free of these problems cannot be found, an array of correction factors can be programmed into the position analyzer to account for the errors (28:501). Lopez, Holle, and Watson of NOAA/ERL/NSSL in Boulder, Colorado, have run the data used in this thesis through a separate position analyzer to correct for errors that may not have been corrected in the field.

Detection Efficiency

In general, the efficiency of a DF will be a function of range. "Large impulses can be detected at great distance, and even small source close to the DF site can saturate the electronics" (28:502). Maier, et al, state that the peak efficiency is 80 to 90% in the 20-120 kilometer interval with a medium gain system. This thesis uses data from a medium gain system at ranges to about 100 kilometers. Operational users at the Cape believe the overall efficiency of the LLP network they use to be 70 to 80% (41).

Appendix B: Percentage of Downtime During 3-Hour Groups at Complex 40 for Various Standoff Distances (Nautical Miles) and Delay Times (Minutes) Based on LLP Data from 1983 and 1984

Table 11. Percentage of Downtime for 3-Hour Groups In July

		3-Hour Period During the Day (Local Standard Time)							
DIS	DEL	00-03	03-06	06-09	09-12	12-15	15-18	18-21	21-24
2.5	6.0	0.000	0.054	0.000	0.000	0.206	0.054	0.054	0.000
2.5	12.0	0.000	0.108	0.000	0.000	0.314	0.143	0.108	0.000
2.5	18.0	0.000	0.161	0.000	0.000	0.376	0.251	0.161	0.000
2.5	24.0	0.000	0.215	0.000	0.000	0.403	0.358	0.215	0.000
2.5	30.0	0.000	0.269	0.000	0.000	0.224	0.466	0.269	0.000
2.5	36.0	0.000	0.323	0.000	0.000	0.224	0.573	0.323	0.000
2.5	42.0	0.000	0.376	0.000	0.000	0.224	0.681	0.358	0.018
2.5	48.0	0.000	0.430	0.000	0.000	0.224	0.789	0.358	0.072
2.5	54.0	0.000	0.484	0.000	0.000	0.224	0.896	0.358	0.125
2.5	60.0	0.000	0.538	0.000	0.000	0.224	1.004	0.358	0.179
5.0	6.0	0.143	0.116	0.000	0.054	0.269	0.072	0.125	0.000
5.0	12.0	0.161	0.224	0.000	0.108	0.323	0.179	0.233	0.000
5.0	18.0	0.215	0.332	0.000	0.161	0.376	0.287	0.296	0.000
5.0	24.0	0.269	0.439	0.000	0.215	0.430	0.394	0.349	0.000
5.0	30.0	0.323	0.547	0.000	0.269	0.224	0.502	0.511	0.045
5.0	36.0	0.376	0.654	0.000	0.323	0.224	0.609	0.565	0.099
5.0	42.0	0.430	0.762	0.000	0.376	0.224	0.717	0.358	0.152
5.0	48.0	0.484	0.869	0.000	0.430	0.224	0.824	0.358	0.206
5.0	54.0	0.538	0.977	0.000	0.484	0.224	0.932	0.358	0.260
5.0	60.0	0.591	1.084	0.000	0.538	0.224	1.039	0.358	0.314
7.5	6.0	0.143	0.215	0.134	0.332	0.421	0.215	0.376	0.000
7.5	12.0	0.161	0.323	0.233	0.556	0.475	0.430	0.591	0.000
7.5	18.0	0.215	0.430	0.287	0.824	0.529	0.645	0.833	0.009
7.5	24.0	0.269	0.538	0.341	1.084	0.582	0.860	0.941	0.116
7.5	30.0	0.323	0.645	0.394	1.308	0.690	1.075	1.039	0.224
7.5	36.0	0.376	0.753	0.448	1.523	0.789	1.290	1.147	0.332
7.5	42.0	0.430	0.860	0.824	1.765	0.878	1.505	1.272	0.439
7.5	48.0	0.484	0.968	0.475	2.034	0.591	1.720	1.013	0.547
7.5	54.0	0.538	1.075	0.475	2.455	0.645	1.935	1.066	0.654
7.5	60.0	0.591	1.183	0.475	2.240	0.699	2.151	1.120	0.762
10.0	6.0	0.753	0.753	0.349	0.627	0.565	0.430	2.222	1.514
10.0	12.0	1.228	1.263	0.708	0.968	0.726	0.806	3.127	2.384
10.0	18.0	1.631	1.819	1.030	1.246	0.842	1.183	3.826	3.082
10.0	24.0	1.900	2.168	1.353	1.514	0.950	1.559	4.265	3.683
10.0	30.0	2.294	2.652	1.676	1.918	1.111	1.935	4.606	4.283
10.0	36.0	2.724	3.136	1.998	2.151	1.272	2.312	5.143	4.767
10.0	42.0	3.154	3.620	2.643	2.446	1.434	2.688	5.538	5.215
10.0	48.0	3.360	4.104	2.563	2.876	1.487	3.065	5.735	5.349

Percent Downtime for July's 3-Hour Groups (Continued)

DIS	DEL	00-03	03-06	06-09	09-12	12-15	15-18	18-21	21-24
		3-Hour Period During the Day (Local Standard Time)							
10.0	54.0	3.683	4.471	2.832	3.154	1.649	3.396	6.066	5.717
10.0	60.0	4.005	4.848	3.100	3.441	1.389	3.719	6.586	6.201
12.5	6.0	1.514	2.384	1.452	1.362	0.977	1.514	3.880	3.082
12.5	12.0	2.312	3.414	2.661	2.159	1.335	2.446	5.063	4.113
12.5	18.0	3.038	4.328	3.593	2.867	1.658	3.118	6.013	4.812
12.5	24.0	3.629	4.955	4.435	3.566	1.980	3.862	6.801	5.502
12.5	30.0	4.059	5.556	5.188	4.400	2.294	4.480	7.590	6.201
12.5	36.0	4.651	6.210	6.039	5.143	2.563	4.892	8.235	6.729
12.5	42.0	5.215	6.819	7.375	5.887	2.832	5.430	8.665	7.195
12.5	48.0	5.932	7.258	7.832	6.631	3.073	5.968	9.229	7.697
12.5	54.0	5.950	7.778	8.459	7.321	3.333	6.461	9.839	8.082
12.5	60.0	6.066	8.262	9.194	7.957	3.091	6.944	10.520	8.548
15.0	6.0	1.640	2.787	1.738	1.810	1.774	1.703	4.032	3.262
15.0	12.0	2.464	4.086	2.966	2.867	2.249	2.885	5.197	4.400
15.0	18.0	3.136	5.152	3.952	3.772	2.590	3.880	6.147	5.206
15.0	24.0	3.880	6.066	4.821	4.606	2.876	4.919	6.935	6.004
15.0	30.0	4.238	6.756	5.627	5.511	3.163	5.833	7.778	6.792
15.0	36.0	4.803	7.536	6.568	6.254	3.432	6.514	8.423	7.428
15.0	42.0	5.421	8.226	8.011	6.998	3.701	7.321	8.880	7.948
15.0	48.0	6.075	8.754	8.575	7.742	4.122	7.885	9.516	8.504
15.0	54.0	6.147	9.382	9.444	8.432	4.391	8.593	10.224	8.943
15.0	60.0	6.326	9.973	10.125	9.041	4.220	9.292	10.896	9.937
17.5	6.0	1.801	3.154	2.419	2.186	2.419	1.846	4.319	3.387
17.5	12.0	2.616	4.570	3.835	3.423	3.029	3.136	5.538	4.597
17.5	18.0	3.306	5.789	5.009	4.435	3.566	4.238	6.541	5.457
17.5	24.0	4.014	6.828	6.084	5.367	4.068	5.332	7.375	6.308
17.5	30.0	4.400	7.625	7.213	6.317	4.588	6.317	8.217	7.151
17.5	36.0	5.036	8.360	8.056	7.186	5.233	7.052	8.916	8.127
17.5	42.0	5.627	9.194	9.606	8.020	5.735	7.912	9.427	8.396
17.5	48.0	6.228	9.776	10.278	8.871	6.344	8.566	10.099	9.023
17.5	54.0	6.756	10.484	11.254	9.624	6.819	9.382	10.806	9.570
17.5	60.0	6.478	11.129	12.043	10.287	7.303	10.188	11.478	10.672
20.0	6.0	2.115	3.387	3.047	2.966	2.984	2.231	4.633	3.602
20.0	12.0	3.199	4.892	4.740	4.194	3.862	3.620	5.995	4.875
20.0	18.0	4.077	6.210	6.138	5.179	4.579	4.722	7.079	5.789
20.0	24.0	4.848	7.464	7.491	6.093	5.116	5.869	7.921	6.694
20.0	30.0	5.412	8.342	8.835	7.097	5.690	6.944	8.853	7.590
20.0	36.0	6.210	9.140	9.857	8.020	6.389	7.787	9.659	8.584
20.0	42.0	6.962	10.108	11.478	8.943	6.953	8.754	10.278	8.853
20.0	48.0	7.724	10.833	12.159	9.857	7.608	9.516	11.425	9.480
20.0	54.0	8.414	11.649	13.181	10.663	8.136	10.439	11.873	10.027
20.0	60.0	8.297	12.401	14.167	11.398	8.719	11.819	12.679	11.129
22.5	6.0	2.348	3.710	4.149	3.530	4.185	3.047	5.090	3.916
22.5	12.0	3.513	5.385	6.084	4.910	5.797	4.848	6.595	5.376
22.5	18.0	4.391	6.989	7.392	6.093	7.312	6.389	7.715	6.505
22.5	24.0	5.161	8.181	8.862	7.168	8.297	7.957	8.611	7.625

Percent Downtime for July's 3-Hour Groups (Continued)

		3-Hour Period During the Day (Local Standard Time)							
DIS	DEL	00-03	03-06	06-09	09-12	12-15	15-18	18-21	21-24
22.5	30.0	5.726	9.176	10.296	8.333	9.391	9.444	9.597	8.737
22.5	36.0	6.828	10.018	11.541	9.373	10.493	10.663	10.457	9.946
22.5	42.0	7.276	11.030	13.235	10.376	11.523	12.052	11.129	10.430
22.5	48.0	8.038	11.783	13.934	11.685	12.419	13.190	12.330	11.272
22.5	54.0	8.728	12.652	15.305	12.608	13.378	14.830	12.841	12.034
22.5	60.0	8.611	13.405	16.398	13.109	14.355	16.066	13.737	13.351
25.0	6.0	2.527	3.987	5.224	3.737	4.919	4.418	5.573	4.310
25.0	12.0	3.746	5.645	7.464	5.099	6.559	6.828	7.330	5.851
25.0	18.0	4.677	7.312	9.238	6.299	8.118	8.656	8.737	7.007
25.0	24.0	5.502	8.486	10.968	7.428	9.211	10.466	9.749	8.091
25.0	30.0	6.165	9.516	12.625	8.683	10.385	12.106	11.004	9.364
25.0	36.0	7.357	10.376	14.346	9.776	11.568	13.423	12.133	10.224
25.0	42.0	8.172	11.443	15.932	10.887	12.643	14.973	13.073	10.851
25.0	48.0	8.674	12.249	16.738	12.267	13.593	16.201	14.498	11.738
25.0	54.0	9.418	13.172	18.217	13.289	14.615	17.832	15.224	12.554
25.0	60.0	9.355	13.978	19.516	13.898	15.591	19.453	16.326	14.041

Table 12. Percentage of Downtime for 3-Hour Groups In August

DIS	DEL	00-03	03-06	06-09	09-12	12-15	15-18	18-21	21-24
		3-Hour Period During the Day (Local Standard Time)							
2.5	6.0	0.054	0.000	0.000	0.000	0.278	0.215	0.108	0.090
2.5	12.0	0.108	0.000	0.000	0.000	0.439	0.269	0.215	0.143
2.5	18.0	0.161	0.000	0.000	0.000	0.600	0.323	0.287	0.197
2.5	24.0	0.215	0.000	0.000	0.000	0.762	0.376	0.341	0.251
2.5	30.0	0.269	0.000	0.000	0.000	0.869	0.430	0.394	0.305
2.5	36.0	0.323	0.000	0.000	0.000	0.977	0.484	0.448	0.358
2.5	42.0	0.376	0.000	0.000	0.000	1.084	0.538	0.502	0.412
2.5	48.0	0.430	0.000	0.000	0.000	1.192	0.591	0.556	0.466
2.5	54.0	0.484	0.000	0.000	0.000	1.299	0.645	0.932	0.556
2.5	60.0	0.538	0.000	0.000	0.000	1.407	0.699	0.986	0.663
5.0	6.0	0.179	0.000	0.000	0.000	1.013	0.573	0.538	0.529
5.0	12.0	0.287	0.000	0.000	0.000	1.398	0.717	0.726	0.744
5.0	18.0	0.394	0.000	0.000	0.000	1.747	0.824	0.753	0.959
5.0	24.0	0.502	0.000	0.000	0.000	2.007	0.932	0.860	1.174
5.0	30.0	0.591	0.018	0.000	0.000	2.222	1.039	1.039	1.389
5.0	36.0	0.645	0.072	0.000	0.000	2.437	1.147	0.869	1.604
5.0	42.0	0.699	0.125	0.000	0.000	2.652	1.254	0.923	1.819
5.0	48.0	0.797	0.179	0.000	0.000	2.867	1.362	0.977	1.935
5.0	54.0	0.905	0.233	0.000	0.000	3.082	1.425	1.461	2.079
5.0	60.0	1.013	0.287	0.000	0.000	3.297	1.478	1.514	2.240
7.5	6.0	0.367	0.000	0.054	0.215	1.685	0.636	0.744	0.896
7.5	12.0	0.609	0.000	0.108	0.323	2.124	0.833	0.878	1.308
7.5	18.0	0.878	0.000	0.161	0.430	2.366	0.995	0.986	1.550
7.5	24.0	1.147	0.000	0.215	0.538	2.581	1.156	1.093	1.765
7.5	30.0	1.380	0.036	0.269	0.645	2.796	1.317	1.201	1.980
7.5	36.0	1.595	0.090	0.323	0.753	3.011	1.478	1.299	2.258
7.5	42.0	1.810	0.143	0.376	0.860	3.226	1.640	1.344	2.473
7.5	48.0	2.025	0.197	0.430	0.968	3.441	1.801	1.102	2.375
7.5	54.0	2.240	0.251	0.484	1.075	3.656	1.918	1.586	2.572
7.5	60.0	2.455	0.305	0.538	1.183	3.871	2.025	1.640	2.787
10.0	6.0	0.448	0.000	0.833	0.977	2.410	1.013	1.962	2.007
10.0	12.0	0.699	0.000	1.210	1.470	3.154	1.416	2.572	2.643
10.0	18.0	0.968	0.000	1.487	1.900	3.674	1.783	3.091	2.993
10.0	24.0	1.461	0.009	1.846	2.303	3.943	2.142	3.602	3.530
10.0	30.0	1.747	0.063	2.061	2.697	4.355	2.437	4.140	3.952
10.0	36.0	2.088	0.116	2.034	3.065	4.767	2.706	4.570	4.220
10.0	42.0	2.151	0.170	2.195	3.387	5.143	2.975	4.910	4.525
10.0	48.0	2.473	0.224	2.357	3.710	5.520	3.244	5.287	4.830
10.0	54.0	2.796	0.278	2.518	4.032	5.896	3.513	5.582	5.242
10.0	60.0	3.118	0.332	2.679	4.355	6.272	3.781	5.726	5.215
12.5	6.0	0.556	0.054	1.111	1.290	3.396	1.443	2.554	2.231
12.5	12.0	0.941	0.108	1.461	1.935	4.211	2.177	3.324	2.948
12.5	18.0	1.317	0.161	1.783	2.437	4.803	2.715	4.032	3.387
12.5	24.0	1.918	0.224	2.195	2.894	5.367	3.306	4.704	4.023
12.5	30.0	2.258	0.332	2.464	3.584	5.896	3.844	5.278	4.516
12.5	36.0	2.652	0.439	2.491	3.763	6.299	4.328	5.806	4.812
12.5	42.0	2.769	0.547	2.706	4.409	6.514	4.713	6.246	5.197

Percent Downtime for August's 3-Hour Groups (Continued)

DIS	DEL	3-Hour Period During the Day (Local Standard Time) 00-03	03-06	06-09	09-12	12-15	15-18	18-21	21-24
12.5	48.0	3.145	0.654	2.921	4.409	6.998	5.108	6.685	5.627
12.5	54.0	3.468	0.762	3.136	4.731	7.482	5.484	7.473	6.030
12.5	60.0	3.790	0.869	3.342	5.063	7.930	5.896	7.760	6.022
15.0	6.0	0.654	0.215	1.290	1.326	4.167	1.774	3.513	3.029
15.0	12.0	1.102	0.430	1.756	2.025	5.251	2.652	4.418	3.737
15.0	18.0	1.532	0.645	2.186	2.536	5.995	3.208	5.099	4.158
15.0	24.0	2.186	0.869	2.706	3.047	6.685	3.862	5.735	4.704
15.0	30.0	2.581	1.138	3.038	3.835	7.330	4.507	6.308	5.143
15.0	36.0	3.029	1.380	3.118	4.122	8.038	5.099	6.837	5.645
15.0	42.0	3.199	1.595	3.333	4.910	8.728	5.609	7.303	6.022
15.0	48.0	3.629	1.810	3.548	4.982	8.987	6.165	7.805	6.505
15.0	54.0	4.005	2.025	3.871	5.466	9.642	6.703	8.656	6.837
15.0	60.0	4.382	2.240	4.077	5.959	10.179	7.276	8.978	7.303
17.5	6.0	0.708	0.421	1.461	1.532	5.278	2.204	3.746	3.495
17.5	12.0	1.210	0.762	2.079	2.294	6.595	3.280	4.588	4.292
17.5	18.0	1.711	1.084	2.670	2.858	7.491	3.934	5.242	4.884
17.5	24.0	2.419	1.416	3.297	3.423	8.297	4.686	5.878	5.538
17.5	30.0	2.867	1.774	3.737	4.229	9.086	5.358	6.452	6.039
17.5	36.0	3.351	2.061	3.925	4.516	9.982	5.950	6.989	6.452
17.5	42.0	3.522	2.330	4.247	5.305	10.744	6.478	7.455	6.882
17.5	48.0	3.952	2.572	4.749	5.376	11.084	7.070	7.948	7.428
17.5	54.0	4.328	2.787	5.179	5.860	11.747	7.661	8.799	7.823
17.5	60.0	4.704	3.002	5.493	6.353	12.697	8.790	9.140	8.324
20.0	6.0	0.950	0.753	1.900	1.676	6.246	3.208	4.337	4.122
20.0	12.0	1.550	1.281	2.769	2.518	7.563	4.462	5.215	5.027
20.0	18.0	2.115	1.703	3.530	3.190	8.522	5.349	5.950	5.600
20.0	24.0	2.823	2.088	4.337	3.862	9.525	6.254	6.586	6.129
20.0	30.0	3.271	2.464	4.991	4.776	10.323	7.079	7.159	6.631
20.0	36.0	3.754	2.787	5.394	5.170	11.192	7.841	7.697	7.079
20.0	42.0	3.925	3.109	5.932	6.066	11.944	8.513	8.351	7.608
20.0	48.0	4.355	3.432	6.649	6.246	12.312	9.633	8.880	8.262
20.0	54.0	4.731	3.754	7.294	6.837	13.118	10.430	9.776	8.826
20.0	60.0	5.108	4.077	7.814	7.446	14.023	11.281	10.161	9.427
22.5	6.0	1.398	1.407	2.599	2.115	8.423	4.875	5.520	4.668
22.5	12.0	2.177	2.249	3.844	3.235	10.547	6.828	6.783	5.780
22.5	18.0	2.894	2.885	4.776	4.185	11.944	8.253	7.778	6.380
22.5	24.0	3.763	3.539	5.744	4.839	12.984	9.910	8.719	6.953
22.5	30.0	4.543	4.229	6.559	5.896	14.220	11.649	9.561	7.482
22.5	36.0	5.224	4.866	7.124	6.452	15.600	12.939	10.421	7.930
22.5	42.0	5.206	5.457	7.823	7.410	16.461	14.310	11.532	8.459
22.5	48.0	5.744	6.048	8.701	7.706	16.846	16.030	12.670	9.149
22.5	54.0	6.228	6.640	9.507	8.548	17.823	17.500	13.880	9.767
22.5	60.0	6.711	7.464	10.690	9.301	18.683	18.405	14.364	10.421
25.0	6.0	2.643	2.124	2.894	2.670	9.803	5.995	6.389	5.224
25.0	12.0	3.925	3.297	4.167	3.987	11.927	8.342	7.876	6.550

Percent Downtime for August's 3-Hour Groups (Continued)

		3-Hour Period During the Day (Local Standard Time)							
DIS	DEL	00-03	03-06	06-09	09-12	12-15	15-18	18-21	21-24
25.0	18.0	4.866	4.265	5.143	5.188	13.486	10.018	9.059	7.294
25.0	24.0	5.995	5.251	6.165	6.075	14.615	11.891	10.125	8.073
25.0	30.0	6.765	6.174	6.998	7.348	15.842	13.728	11.075	8.790
25.0	36.0	7.572	7.025	7.563	8.118	17.410	15.063	12.007	9.489
25.0	42.0	7.948	7.832	8.262	9.211	18.710	16.694	13.127	10.242
25.0	48.0	8.701	8.638	9.140	9.615	19.265	18.647	13.987	11.093
25.0	54.0	9.310	9.444	9.946	10.851	19.642	20.305	15.215	11.900
25.0	60.0	9.901	10.959	11.183	11.694	20.663	21.344	15.797	12.697

Appendix C: Computer Simulation Code

The following SLAM II program drives the FORTRAN subroutines to simulate 6 years of lightning events used in this thesis. Some comments are provided, but most explanations for why particular values are used are in the text.

SLAM II Code

```
GEN,DHOLLAND,LIGHTNING SIMULATION,09/27/88,6,N,N,,N,,72;
LIMITS,2,2,100;
NETWORK;
      CREATE,UNF(0,2),0,,500,1;   Storms are created, then assigned
      ACT/1,0,0.00493421,L1;      to a date/time group according to
      ACT/2,0,0.00082237,L2;      the probabilities in Table 8.
      ACT/3,0,0.00164474,L3;
      ACT/4,0,0.00575658,L4;
      ACT/5,0,0.01562500,L5;
      ACT/6,0,0.00822368,L6;
      ACT/7,0,0.00657895,L7;
      ACT/8,0,0.00328947,L8;
      ACT/9,0,0.00378644,L9;
      ACT/10,0,0.00004733,L10;
      ACT/11,0,0.00236653,L11;
      ACT/12,0,0.00804619,L12;
      ACT/13,0,0.02887164,L13;
      ACT/14,0,0.03597122,L14;
      ACT/15,0,0.03265808,L15;
      ACT/16,0,0.01325256,L16;
      ACT/17,0,0.00414541,L17;
      ACT/18,0,0.00207270,L18;
      ACT/19,0,0.00466358,L19;
      ACT/20,0,0.00984534,L20;
      ACT/21,0,0.03627232,L21;
      ACT/22,0,0.07409917,L22;
      ACT/23,0,0.05855389,L23;
      ACT/24,0,0.01347258,L24;
      ACT/25,0,0.00370370,L25;
      ACT/26,0,0.00046296,L26;
      ACT/27,0,0.00601852,L27;
      ACT/28,0,0.01203704,L28;
      ACT/29,0,0.05555556,L29;
      ACT/30,0,0.09351853,L30;
      ACT/31,0,0.05879630,L31;
      ACT/32,0,0.01990741,L32;
```

```
         ACT/33,0,0.00696998,L33;
         ACT/34,0,0.00696998,L34;
         ACT/35,0,0.00428922,L35;
         ACT/36,0,0.01501225,L36;
         ACT/37,0,0.04503676,L37;
         ACT/38,0,0.07988664,L38;
         ACT/39,0,0.04664522,L39;
         ACT/40,0,0.01393995,L40;
         ACT/41,0,0.01633121,L41;
         ACT/42,0,0.01059322,L42;
         ACT/43,0,0.00794492,L43;
         ACT/44,0,0.00750353,L44;     L1 to L48 are used to assign
         ACT/45,0,0.02913136,L45;     values for the time of day (XX(1)),
         ACT/46,0,0.03663489,L46;     day of year (XX(2)), and month
         ACT/47,0,0.03001412,L47;     (XX(3)).  Then, FORTRAN routines
         ACT/48,0,0.01809675,L48;     are used.
L1       ASSIGN,XX(1)=UNF(0,180),XX(2)=UNF(90,119.999),XX(3)=4;
         ACT;
         EVENT,1;
         TERM;
L2       ASSIGN,XX(1)=UNF(180,360),XX(2)=UNF(90,119.999),XX(3)=4;
         ACT;
         EVENT,2;
         TERM;
L3       ASSIGN,XX(1)=UNF(360,540),XX(2)=UNF(90,119.999),XX(3)=4;
         ACT;
         EVENT,3;
         TERM;
L4       ASSIGN,XX(1)=UNF(540,720),XX(2)=UNF(90,119.999),XX(3)=4;
         ACT;
         EVENT,4;
         TERM;
L5       ASSIGN,XX(1)=UNF(720,900),XX(2)=UNF(90,119.999),XX(3)=4;
         ACT;
         EVENT,5;
         TERM;
L6       ASSIGN,XX(1)=UNF(900,1080),XX(2)=UNF(90,119.999),XX(3)=4;
         ACT;
         EVENT,6;
         TERM;
L7       ASSIGN,XX(1)=UNF(1080,1260),XX(2)=UNF(90,119.999),XX(3)=4;
         ACT;
         EVENT,7;
         TERM;
L8       ASSIGN,XX(1)=UNF(1260,1440),XX(2)=UNF(90,119.999),XX(3)=4;
         ACT;
         EVENT,8;
         TERM;
L9       ASSIGN,XX(1)=UNF(0,180),XX(2)=UNF(120,150.999),XX(3)=5;
         ACT;
         EVENT,9;
         TERM;
L10      ASSIGN,XX(1)=UNF(180,360),XX(2)=UNF(120,150.999),XX(3)=5;
```

```
        ACT;
        EVENT,10;
        TERM;
L11     ASSIGN,XX(1)=UNF(360,540),XX(2)=UNF(120,150.999),XX(3)=5;
        ACT;
        EVENT,11;
        TERM;
L12     ASSIGN,XX(1)=UNF(540,720),XX(2)=UNF(120,150.999),XX(3)=5;
        ACT;
        EVENT,12;
        TERM;
L13     ASSIGN,XX(1)=UNF(720,900),XX(2)=UNF(120,150.999),XX(3)=5;
        ACT;
        EVENT,13;
        TERM;
L14     ASSIGN,XX(1)=UNF(900,1080),XX(2)=UNF(120,150.999),XX(3)=5;
        ACT;
        EVENT,14;
        TERM;
L15     ASSIGN,XX(1)=UNF(1080,1260),XX(2)=UNF(120,150.999),XX(3)=5;
        ACT;
        EVENT,15;
        TERM;
L16     ASSIGN,XX(1)=UNF(1260,1440),XX(2)=UNF(120,150.999),XX(3)=5;
        ACT;
        EVENT,16;
        TERM;
L17     ASSIGN,XX(1)=UNF(0,180),XX(2)=UNF(151,180.999),XX(3)=6;
        ACT;
        EVENT,17;
        TERM;
L18     ASSIGN,XX(1)=UNF(180,360),XX(2)=UNF(151,180.999),XX(3)=6;
        ACT;
        EVENT,18;
        TERM;
L19     ASSIGN,XX(1)=UNF(360,540),XX(2)=UNF(151,180.999),XX(3)=6;
        ACT;
        EVENT,19;
        TERM;
L20     ASSIGN,XX(1)=UNF(540,720),XX(2)=UNF(151,180.999),XX(3)=6;
        ACT;
        EVENT,20;
        TERM;
L21     ASSIGN,XX(1)=UNF(720,900),XX(2)=UNF(151,180.999),XX(3)=6;
        ACT;
        EVENT,21;
        TERM;
L22     ASSIGN,XX(1)=UNF(900,1080),XX(2)=UNF(151,180.999),XX(3)=6;
        ACT;
        EVENT,22;
        TERM;
L23     ASSIGN,XX(1)=UNF(1080,1260),XX(2)=UNF(151,180.999),XX(3)=6;
        ACT;
```

```
      EVENT,23;
      TERM;
L24   ASSIGN,XX(1)=UNF(1260,1440),XX(2)=UNF(151,180.999),XX(3)=6;
      ACT;
      EVENT,24;
      TERM;
L25   ASSIGN,XX(1)=UNF(0,180),XX(2)=UNF(181,211.999),XX(3)=7;
      ACT;
      EVENT,25;
      TERM;
L26   ASSIGN,XX(1)=UNF(180,360),XX(2)=UNF(181,211.999),XX(3)=7;
      ACT;
      EVENT,26;
      TERM;
L27   ASSIGN,XX(1)=UNF(360,540),XX(2)=UNF(181,211.999),XX(3)=7;
      ACT;
      EVENT,27;
      TERM;
L28   ASSIGN,XX(1)=UNF(540,720),XX(2)=UNF(181,211.999),XX(3)=7;
      ACT;
      EVENT,28;
      TERM;
L29   ASSIGN,XX(1)=UNF(720,900),XX(2)=UNF(181,211.999),XX(3)=7;
      ACT;
      EVENT,29;
      TERM;
L30   ASSIGN,XX(1)=UNF(900,1080),XX(2)=UNF(181,211.999),XX(3)=7;
      ACT;
      EVENT,30;
      TERM;
L31   ASSIGN,XX(1)=UNF(1080,1260),XX(2)=UNF(181,211.999),XX(3)=7;
      ACT;
      EVENT,31;
      TERM;
L32   ASSIGN,XX(1)=UNF(1260,1440),XX(2)=UNF(181,211.999),XX(3)=7;
      ACT;
      EVENT,32;
      TERM;
L33   ASSIGN,XX(1)=UNF(0,180),XX(2)=UNF(212,242.999),XX(3)=8;
      ACT;
      EVENT,33;
      TERM;
L34   ASSIGN,XX(1)=UNF(180,360),XX(2)=UNF(212,242.999),XX(3)=8;
      ACT;
      EVENT,34;
      TERM;
L35   ASSIGN,XX(1)=UNF(360,540),XX(2)=UNF(212,242.999),XX(3)=8;
      ACT;
      EVENT,35;
      TERM;
L36   ASSIGN,XX(1)=UNF(540,720),XX(2)=UNF(212,242.999),XX(3)=8;
      ACT;
      EVENT,36;
```

```
        TERM;
 L37    ASSIGN,XX(1)=UNF(720,900),XX(2)=UNF(212,242.999),XX(3)=8;
        ACT;
        EVENT,37;
        TERM;
 L38    ASSIGN,XX(1)=UNF(900,1080),XX(2)=UNF(212,242.999),XX(3)=8;
        ACT;
        EVENT,38;
        TERM;
 L39    ASSIGN,XX(1)=UNF(1080,1260),XX(2)=UNF(212,242.999),XX(3)=8;
        ACT;
        EVENT,39;
        TERM;
 L40    ASSIGN,XX(1)=UNF(1260,1440),XX(2)=UNF(212,242.999),XX(3)=8;
        ACT;
        EVENT,40;
        TERM;
 L41    ASSIGN,XX(1)=UNF(0,180),XX(2)=UNF(243,272.999),XX(3)=9;
        ACT;
        EVENT,41;
        TERM;
 L42    ASSIGN,XX(1)=UNF(180,360),XX(2)=UNF(243,272.999),XX(3)=9;
        ACT;
        EVENT,42;
        TERM;
 L43    ASSIGN,XX(1)=UNF(360,540),XX(2)=UNF(243,272.999),XX(3)=9;
        ACT;
        EVENT,43;
        TERM;
 L44    ASSIGN,XX(1)=UNF(540,720),XX(2)=UNF(243,272.999),XX(3)=9;
        ACT;
        EVENT,44;
        TERM;
 L45    ASSIGN,XX(1)=UNF(720,900),XX(2)=UNF(243,272.999),XX(3)=9;
        ACT;
        EVENT,45;
        TERM;
 L46    ASSIGN,XX(1)=UNF(900,1080),XX(2)=UNF(243,272.999),XX(3)=9;
        ACT;
        EVENT,46;
        TERM;
 L47    ASSIGN,XX(1)=UNF(1080,1260),XX(2)=UNF(243,272.999),XX(3)=9;
        ACT;
        EVENT,47;
        TERM;
 L48    ASSIGN,XX(1)=UNF(1260,1440),XX(2)=UNF(243,272.999),XX(3)=9;
        ACT;
        EVENT,48;
        TERM;
        END;
INIT,0,325;
FIN;
```

```
      PROGRAM MODEL
      DIMENSION NSET(10000)
      DOUBLE PRECISION PIE,CLAT,CLON,FLAT,FLON,A,B,C,D
      INCLUDE 'PARAM.INC'
      COMMON/SCOM1/ATRIB(MATRB), DD(MEQT), DDL(MEQT), DTNOW, II, MFA,
     1MSTOP, NCLNR, NCRDR, NPRNT, NNRUN, NNSET, NTAPE, SS(MEQT),
     2SSL(MEQT),TNEXT,TNOW,XX(MMXXV),PIE,FLAT,FLON,CLAT,CLON,A,B,C,D
      COMMON QSET(10000)
      EQUIVALENCE (NSET(1),QSET(1))
      OPEN (UNIT=8,FILE='GS088D:[DHOLLAND]SIM.SET',STATUS='NEW')
      OPEN (UNIT=9,FILE='PARAM.SET',STATUS='NEW')
      NNSET=10000
      NCRDR=5
      NPRNT=6
      NTAPE=7
      NPLOT=2
      PIE=3.1415926535898/180.
      CALL SLAM
      STOP
      END
C
      SUBROUTINE EVENT(I)
      INCLUDE 'PARAM.INC'
      COMMON/SCOM1/ATRIB(MATRB), DD(MEQT), DDL(MEQT), DTNOW, II, MFA,
     1MSTOP,NCLNR, NCRDR, NPRNT, NNRUN, NNSET, NTAPE, SS(MEQT),
     2SSL(MEQT),TNEXT,TNOW,XX(MMXXV),PIE,FLAT,FLON,CLAT,CLON,A,B,C,D
C
C DETERMINE DURATION, SIZE, POSITION, FLASH RATE
C
   10 DURATION=RLOGN(112.8,90.46,1)
      IF (DURATION.GT.350.) GOTO 10
      SMODE=DURATION**(1./2.4)
      IF (SMODE.LT.2.) GOTO 10
      SIZE=TRIAG(2.,SMODE,12.,2)
      RSQ=(30.+SIZE)**2
      RANGE=SQRT(UNFRM(0.,RSQ,3))/60.
      BERING=UNFRM(0.,6.283185307,4)
      CLAT=28.562+RANGE*SIN(BERING)
      CLON=80.577-RANGE*COS(BERING)/.8783
   20 RATE=RLOGN(2.543,3.122,5)
       IF (RATE.GT.18.0) GOTO 20
       IF (RATE.GT.12.0.AND.DURATION.GT.250.) GOTO 20
      SUM=0.
      COUNT=0
      FLAG=0.
      IYY=NNRUN
      MON=XX(3)
      JD=XX(2)
C
C  DETERMINE TIME OF FIRST FLASH
```

```
C
      FFLASH=1440*JD+XX(1)-DURATION/2.
      IF (DURATION/2.GT.XX(1)) JD=JD-1
      FLASH=FFLASH
C
C  CHECK FOR STORM BEING ON THE LAST DAY OF THE MONTH
C
      IF (JD.EQ.119.OR.JD.EQ.150.OR.JD.EQ.180.OR.JD.EQ.211.OR.
     +    JD.EQ.242.OR.JD.EQ.272) THEN FLAG=1.
C
C  CHECK FOR END OF STORM
C
  100 IF (SUM.LT.DURATION) THEN
       COUNT=COUNT+1
C
C  SCHEDULE FLASH AND ASSIGN ITS TIME OF DAY.
C  INCREMENT DAY IF NECESSARY
C
       TINC=EXPON(1./RATE,6)
       SUM=SUM+TINC
       FLASH=FLASH+TINC
       JM=FLASH
       TMIN=FLASH-(JD-1)*1440
       IF (TMIN.GT.1440.) THEN
        JD=JD+1
        TMIN=FLASH-(JD-1)*1440
        IF (FLAG.EQ.1) MON=MON+1
       ENDIF
       HH=TMIN/60.
       IHH=TMIN/60
       XMIN=(HH-IHH)*60.
       MM=(HH-IHH)*60
       ISS=(XMIN-MM)*60
C
C  ASSIGN MINUTE--ROUND UP IF OVER 30 SECONDS
C
       IF (ISS.GT.30) JM=JM+1
C
C  ASSIGN MONTH BASED ON JULIAN MINUTE (LEAP YEARS NOT USED)
C
       IF (JM.LE.129600) MON=3
       IF (JM.GT.129600) MON=4
       IF (JM.GT.172800) MON=5
       IF (JM.GT.217440) MON=6
       IF (JM.GT.260640) MON=7
       IF (JM.GT.305280) MON=8
       IF (JM.GT.349920) MON=9
C
C  ASSIGN POSITION OF STROKE WITHIN STORM
C
       R1=TRIAG(0.,SIZE/4.,SIZE+1.,7)/60.
       B1=UNFRM(0.,6.283185307,8)
       FLAT=CLAT+R1*SIN(B1)
```

```
      FLON=CLON-R1*COS(B1)*COS(CLAT*PIE)
      A=28.562*PIE
      B=80.577*PIE
      C=FLAT*PIE
      D=FLON*PIE
      ARG=SIN(A)*SIN(C)+COS(A)*COS(C)*COS(B-D)
C
C  ROUNDING CAN LET "ARG" BE GREATER THAN 1. DON'T LET THAT HAPPEN
C
      IF (ARG.GT.1.) ARG=1.
      R=3436.87*ACOS(ARG)
C
C  WRITE YEAR, MONTH, JULIAN MINUTE AND RANGE TO A FILE
C
      WRITE (8,1000) IYY,MON,JM,R
      GOTO 100
     ENDIF
 1000 FORMAT(1X,I2,1X,I2,1X,I6,1X,F4.1)
      IFL=FFLASH
      ICNT=COUNT
C
C  WRITE STORM'S STATISTICS TO A FILE
C
      WRITE (9,2000) NNRUN,MON,JD,IFL,CLAT,CLON,RANGE*60.,BERING/PIE,
     +               DURATION,RATE,SIZE,ICNT
 2000 FORMAT (1X,I2,1X,I2,1X,I3,1X,I6,1X,F6.3,1X,F6.3,1X,F5.1,
     +        1X,F5.1,1X,F6.2,1X,F4.1,1X,F4.1,1X,I4)
      RETURN
      END
C
      SUBROUTINE OTPUT
      INCLUDE 'PARAM.INC'
      COMMON/SCOM1/ATRIB(MATRB), DD(MEQT), DDL(MEQT), DTNOW, II, MFA,
     1MSTOP, NCLNR, NCRDR, NPRNT, NNRUN, NNSET, NTAPE, SS(MEQT),
     2SSL(MEQT), TNEXT, TNOW, XX(MMXXV)
C
C  TO MAKE EACH YEAR SEPARATE, CLOSE THE FILE AND THEN OPEN IT AGAIN
C  THIS MAKES THE DATA EASIER TO WORK WITH SINCE ALL THE DATA MUST BE
C  SORTED CHRONOLOGICALLY.
C
      CLOSE (UNIT=8)
      OPEN (UNIT=8,FILE='GSO88D:[DHOLLAND]SIM.SET',STATUS='NEW')
      RETURN
      END
```

Parameters Used in the FORTRAN Subroutines

The parameters used in the FORTRAN subroutines are in a file called "PARAM.INC." That file was copied from system files and is listed below.

```
C
C  MATERIAL HANDLING EXTENSION VERSION 2.1 PARAMETERS
C
      PARAMETER (MXCRN=20,  MXSPA=75,  MXPIL=200, MXTRK=10,
     1           MXCPR=10,  MXYLOC=21000, MXVCPO=160,
     2           MXVSEG=200,MXVSET=10,MXVUNI=50)
C
C  SLAM II REGULAR VERSION PARAMETERS
C
      PARAMETER (MEQT=100,  MSCND=25, MENTR=50,  MRSC=75, MARR=50,
     1  MGAT=25, MHIST=50, MCELS=500, MCLCT=50, MSTAT=50,MEQV=100,
     2  MATRB=100, MFILS=100, MPLOT=10,  MVARP=10,  MSTRM=10,
     3  MACT=100, MNODE=500, MITYP=50, MMXXV=100, MMXFLD=50)
      PARAMETER ( MAXLVL=50,MXMACS=20,MXBRKS=10)
C
      PARAMETER (MVARP1=MVARP+1)
```

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Vita

Captain Donald E. Holland [redacted] in 1976, [redacted]attended Harding University in Searcy, Arkansas where, in 1980, he received the degrees of Bachelor of Science in Physics and Mathematics and Bachelor of Arts in Bible and Religion. Upon graduation, he worked as a field engineer for Schlumberger Well Services in Lafayette, Louisiana, and as a technical sales representative for Hinds International, Inc. in Portland, Oregon. He entered the Air Force in February 1984 as part of the Air Weather Service and attended the Basic Meteorology Program at San Jose State University from May 1984 to May 1985 as part of the Air Force Institute of Technology Civilian Institute Program. In May 1985, he was assigned to Detachment 11, Second Weather Squadron at Patrick Air Force Base, Florida, where he provided weather support for the Eastern Test Range and the Air Force Technical Applications Center, until entering the School of Engineering, Air Force Institute of Technology, in June 1987.

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The purpose of this study was to review the current set of lightning launch constraints being used by NASA, the ~~U.S.~~ Air Force, and the U.S. Navy. The study had 3 primary objectives: (1) Assimilate current knowledge about triggered lightning to aerospace systems, and how lightning launch constraints are used to make launching safer: (2) Analyze cloud-to-ground lightning in the Cape Canaveral, FL, area for spatial and diurnal distributions and for its impact on launch availability; (3) Develop a model to simulate all lightning events to better determine launch availabilities based on the first constraint.

The study found that the lightning activity in the Cape area is not uniformly distributed in time or space. There is a well-known afternoon peak in activity, plus, there are areas where lightning occurs with much greater frequency--especially with low-level winds from the southwest. Since the launch constraints specify standoff distances and delay times from naturally occurring lightning, launch availability is a function of time of year, time of day, and launch site. From the simulation model, equations were derived to define launch availability as a function of standoff distance and delay time for each summer month (Apr-Sep) and each 3-hour group (e.g. 0000-0300 Local Standard Time) in July and August. Keywords: [illegible], Launching constraints, [illegible], Theses, (edc)